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Governance of Greenwashing Behaviors: A Perspective of Heterogeneous Firm Types

Yi Zhang [1], Huiming Zhang [2], Kai Wu [3] and Danyun Shen [4,*]

1 School of Management Science and Engineering, Nanjing University of Information Science & Technology, Nanjing 210044, China; 20211224031@nuist.edu.cn
2 Institute of Climate Economy and Low-Carbon Industry, Nanjing University of Information Science & Technology, Nanjing 210044, China; hm.zhang_16@163.com
3 School of Finance, Central University of Finance and Economics, Beijing 100081, China; wukai8759@cufe.edu.cn
4 School of Applied Technology, Nanjing University of Information Science & Technology, Nanjing 210044, China
* Correspondence: 880109@nuist.edu.cn; Tel.: +86-15366162453

Abstract: Corporate greenwashing in response to carbon neutrality strategies has received substantial academic attention. Distinct from previous studies, this paper establishes a differential game model incorporating both green and brown enterprise types. The model compares greenness and total profits under two government scenarios: subsidies for green enterprises and the regulation of brown enterprises. It further analyzes the mechanism behind brown enterprise greenwashing formation. The results show that subsidies alone encourage brown enterprises to engage in greenwashing. However, government regulation inhibits such behaviors, with the inhibition effect positively correlated to regulatory intensity. Consumers' green perception of enterprises also significantly drives brown enterprise greenwashing degrees. Higher green enterprise perception coefficients reduce greenwashing, while higher brown enterprise perception coefficients increase it. Differential game and simulation analyses reveal that greenwashing governance should consider both direct policy effects on brown enterprises and indirect subsidy effects on green enterprises.

Keywords: corporate greenwashing; brown enterprises; subsidies; regulatory intensity; differential game

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Citation: Zhang, Y.; Zhang, H.; Wu, K.; Shen, D. Governance of Greenwashing Behaviors: A Perspective of Heterogeneous Firm Types. *Energies* **2024**, *17*, 1340. https://doi.org/10.3390/en17061340

Academic Editor: Peter V. Schaeffer

Received: 11 January 2024
Revised: 28 February 2024
Accepted: 1 March 2024
Published: 11 March 2024

1. Introduction

Carbon neutrality has become an important global initiative in response to climate change and energy transformation. In China, the 20th National Congress of the Communist Party further emphasized actively yet prudently promoting 'dual-carbon' targets, presenting new requirements for corporate environmental practices. From a purchase decision perspective, as environmental issues become more prominent, public awareness has grown, and stakeholders have strengthened environmental considerations [1]. Consumers desire green products and experience spillover effects from pro-environmental behaviors, increasing a willingness to pay green premiums [2]. On the production side, green consumer preferences may compel producers and suppliers to enhance product greenness [3]. For instance, energy companies face increasing stakeholder pressure to provide sustainable and clean energy products [4]. With ESG investment growth, companies now emphasize ESG performance to build responsible green development reputations favored by markets and consumers.

However, when actively implementing carbon neutrality and responding to purchase decisions, some enterprises have engaged in 'greenwashing', exaggerating ESG efforts and contributions, especially regarding environmental protection, through false or misleading information [5]. Such behaviors damage corporate reputations and stock performance while negatively impacting consumer purchases, creating a 'lemon market' problem [6].

Examples such as Volkswagen, Northern Pharmaceutical, Coca-Cola, Nike, and Allbirds highlight the urgent need for governance.

Current research on governing corporate greenwashing as a critical environmental policy issue has attracted substantial academic attention. The relevant literature focuses on:

- Green behavior game research. Domestic and foreign scholars have expanded green technology innovation research to green supply chain management, examining how chains can provide green products meeting environmental and sustainability needs [7]. Game models are increasingly applied in green supply chain research, with evolutionary games used to simulate collaborative emission-reduction stability trends [8] and explore emerging corporate green behaviors [9]. However, evolutionary games use static frameworks without considering corporate operational continuity. Some scholars have since studied green supply chain issues under a dynamic framework using differential game models [10]. Ma used a differential game for manufacturing-retailer technological investment and cooperation strategy decisions [11].
- Greenwashing motivation analysis. Different perspectives have been used to study motivations. From a neoclassical economics view, enterprises are profit-seeking, maximizing self-interest and minimizing costs. Thus, greenwashing is a rational corporate strategy development choice influenced by competitive pressures and opportunities [12]. Environmental policy requirements [13] and consumer demand [3] have become important greenwashing drivers. From an information economics view, consumers have limited green market cognition, causing information asymmetry [14]. Imperfect regulations enable greenwashing through certification loopholes [15]. A stakeholder view categorizes motivations as external market/non-market factors (consumers, policies, etc.) [16,17] and internal factors such as age, size, debt, performance, and values [18]. Stakeholder activism also motivates greenwashing [19].
- Greenwashing governance research. Environmental certifications and reductions provide constraints, but governance relies on government actions [20,21]. As corporate behaviors, experts apply market failure, natural monopoly, and information asymmetry theories to study greenwashing market rules. Governments can regulate to maintain stability. Under ideal conditions, enterprises adopt environmental philosophies within policy goals [22]. Research shows that green credit governance effectively deters greenwashing [13], while central inspections reduce misconduct, indicating that standardized central governance is needed [23]. Some current research focusing on addressing greenwashing emphasizes the effects of third-party certification [24]. Certification standards and systems have provided recognized benchmarks for green market competition and corporate sustainability to some innovative extent, but apparently, such labels and certifications have little effect on the market order under conditions of market competition and regulatory absence [25]. Therefore, strictly regulating certification systems, strengthening supervision and publicity, and increasing monitoring channels will be key to enhancing the authority and credibility of green certifications and strengthening consumer awareness and governance of corporate greenwashing [26].

Media oversight also plays an important role in eliminating greenwashing companies. Media coverage as a form of external supervision can have an inhibitory effect on greenwashing behaviors [27]. However, current governance of greenwashing remains "joint" governance rather than "collaborative" governance. When cooperation between the government and media is strengthened, corporate hidden behaviors will be inhibited, improving the effectiveness of greenwashing governance and achieving "synergy" [28].

The above literature indicates that establishing government regulatory systems is critical for greenwashing governance. However, even in developed countries with relatively strong environmental awareness like the United States, monitoring involves uncertain enforcement [16]. Such non-binding guidelines are insufficient to protect consumers from greenwashing harm [29]. In China, punitive regulations provide policy support to curb illegal greenwashing, yet industries still exaggerate or mislead in online green marketing claims. Thus, governance may require considering regulatory intensity, and monitoring should be supplemented with other approaches.

In summary, existing research has conducted beneficial greenwashing governance exploration, laying the foundation for this study. Using a Stackelberg differential game model, this paper examines greenwashing governance from a green supply chain perspective, incorporating corporate heterogeneity and government governance modes. First, internal greenwashing motivations are important. Different stakeholder pressures [30], political relationships [31] and environmental awareness [32] determine green strategy preferences. Thus, this paper divides enterprises into green firms that do not greenwash and brown firms that may greenwash for profit. Second, different government approaches such as subsidies and regulations are incorporated into the model.

Marginal innovations versus the existing literature include: (1) Unlike models with a single enterprise type [33,34], this paper incorporates heterogeneity, as policies targeting one type may also impact others' greenwashing, informing anti-greenwashing policies. (2) Most research uses static frameworks [35,36], while this paper introduces a differential game model studying greenwashing formation, adding upstream suppliers for practical governance insights. (3) Whereas studies conclude that subsidies benefit low-carbon enterprises, encouraging their use [37], this research finds that subsidies alone may increase brown enterprise greenwashing.

The remainder of the paper is structured as follows. Section 2 outlines the modeling assumptions. Section 3 analyzes and discusses the equilibrium results from modeling three periods. Section 4 simulates the equilibrium results of different decision models through numerical simulation and discusses the factors influencing green drift. Finally, Section 5 concludes the paper and offers policy recommendations.

2. Model Assumptions

First, the following assumptions are made for the model:

Assumption 1. Considering corporate heterogeneity, this paper studies a green supply chain with one manufacturer (green enterprise U) and one retailer (brown enterprise D). Manufacturer U provides green products on a wholesale basis to retailer D. Retailer D sells both U's green products and its own non-green brands with lower greenness. Consumer purchases are influenced by factors including price, green perception, and brand reputation.

Assumption 2. U's greenness level for its products is $g_U(t), t \in [0, \infty), g_D(t) \le g_U(t)$, and U's wholesale price is P. D's greenness level is g_D. D's sale price for its own brand is $P_D(t) = \alpha g_D(t)$, and for U's green product it is $P_U(t) = \beta g_U(t)$. Fixed costs for U and D are unchanged. With green R&D investment as the focus, other costs such as equipment and labor are not yet considered. Thus, marginal costs are $C_U = c_U g_U(t)$, $C_D = c_D g_D(t)$.

Assumption 3. D's greenwashing variable is based on the nature and form of greenwashing. Some companies invest in green marketing to be perceived as environmentally friendly despite limited environmental performance. They advertise to improve purchase intentions and brand attitudes [38]. "Greenwashing" refers to misleading consumers about a company's environmental practices or a product's benefits [16]. There are two forms: making green claims and executing greenwashing. Most literature examines making claims, while executing greenwashing is less studied [39]. D can influence green perceptions and reputation via promotions [40]. Since making claims is prevalent, this paper introduces false advertising intensity as the greenwashing variable measuring the degree of greenwashing. D controls its false green promotion level $A(t)$, with costs $\frac{1}{2}\rho A(t)^2$ [41].

Assumption 4. D's false promotion positively impacts its brand reputation [40]. Brand image (reputation) dynamics are denoted by $G(t)$, with dynamics [42]:

$$\dot{G}(t) = \theta A(t) - \delta G(t), \quad G(0) = G_0 > 0 \tag{1}$$

where $G(t)$ denotes the brand reputation of green products at time t, and $\theta > 0$ is a positive parameter measuring the impact of D's degree of greenwashing on the brand image; $\delta > 0$ is the decay rate of the brand image.

Assumption 5. Consumers' choices are influenced by their green perception of the product. Green perception is positively correlated with green value and marketing [43]. Consumers' green perceptions for the two enterprises are: $S_U(t) = k_1 g_U(t)$, where k_* are positive parameters measuring consumers' own green perception coefficients for the products.

Assumption 6. Demand Q_* negatively depends on price $P_*(t)$ and the environmental reputation (green reputation) $G(t)$ of the competing enterprise, and it positively depends on its own environmental reputation (green reputation) $G(t)$. It is also influenced by competition between U's product and D's own brand. The demand functions for U and D take the following linear forms [41]:

$$Q_U(g_U, A, G, P_U) = \gamma[S_U(t) - S_D(t)] - G(t) - P_U(t) \tag{2}$$

$$Q_D(g_U, A, G, P_U) = \varphi[S_D(t) - S_U(t)] + G(t) - P_D(t) \tag{3}$$

where γ, φ are the competition coefficients between the two commodities.

Based on the above assumptions, the objective functions of the green enterprise and brown enterprise are:

$$\max_{g_U} \pi_U = \int_0^\infty e^{-rt} \{(P - C_U)Q_U\} dt \tag{4}$$

$$\max_{A, g_D} \pi_D = \int_0^\infty e^{-rt} \left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2\right\} dt \tag{5}$$

3. Model Construction and Solution

3.1. Benchmark Model under Free Competition (Model B)

The benchmark model considers the situation without government regulation, where the market only has a green enterprise and a brown enterprise as decision makers, both aiming to maximize their own profits. The objective functions of the two enterprises are:

$$\max_{g_U} \pi_U = \int_0^\infty e^{-rt} \{(P - C_U)Q_U\} dt \tag{6}$$

$$\max_{A, g_D} \pi_D = \int_0^\infty e^{-rt} \left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2\right\} dt \tag{7}$$

Proposition 1.

- The optimal greenness trajectory of the brown enterprise is $g_D^{B*} = \frac{(1-k_2)k_1\gamma+\alpha\varphi}{2\beta(\alpha - k_1\gamma)(\beta - c_d)} e^{-rt} - \frac{k_1+\alpha(P-\alpha k_1)+(1+k_2)\varphi}{2(\varphi^2-\theta k_1)}$, the optimal greenness trajectory of the green enterprise is $g_D^{B*} = \frac{(1-k_1)\alpha k_1\gamma+(P-\alpha-k_1\gamma)}{2(\varphi^2-\theta k_1- c_d)} e^{-rt} + \frac{(1- k_1\gamma+ k_2)\alpha-k_2\gamma}{\varphi^2-\theta k_1}$;
- The degree of greenwashing by the brown enterprise is $A^{B*} = \frac{(P- k_1\gamma)\varphi+\alpha(\theta k_1- c_d)+\theta}{2\beta^2(\alpha - k_1\gamma)} + \frac{P-\alpha k_1}{\beta- k_2\varphi} - 2(\varphi^2 - \theta k_1)$;
- The optimal trajectory of the brand reputation of the brown enterprise is $G^{B*} = [G_0 - \frac{\theta}{\delta}A]e^{-\delta t} + \frac{\theta}{\delta}A$;
- The optimal profit value function of the green enterprise is $V_D^{B*}(G) = m_1^B G^2 - m_2^B G + m_3^B$, $V_U^{B*}(G) = t_1^B G^2 - t_2^B G + t_3^B$, where m_*^B, t_*^B in proof.

Proof 1. The Hamiltonian function of Enterprise D is:

$$rV_D(G) = \max_{A, g_D}\left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2 + V'_D(\theta A - \delta G)\right\} \tag{8}$$

Taking the partial derivatives of A and g_D, respectively, in the above equation and setting them to 0 yields:

$$A = \frac{\theta V'_D - g_D k_2 \varphi(P - \alpha g_D + c_D g_D)}{\rho} \tag{9}$$

$$g_D(t) = \frac{G - g_U k_1 \varphi}{2(\alpha - A k_2 \varphi)} + \frac{P}{2(\alpha - c_D)} \tag{10}$$

The Hamiltonian function of Enterprise U is:

$$rV_U(G) = \max_{g_U}\left\{(P - C_U)Q_U + V'_U(\theta A - \delta G)\right\} \tag{11}$$

Substituting the above two equations into the Hamiltonian function of Enterprise U, taking the partial derivative of g_U and setting it to 0 yields:

$$g_U(t) = \frac{P}{2c_U} - \frac{G + \gamma A\, g_D k_2}{2(\beta - k_1\gamma)} \tag{12}$$

Combining g_U, g_D and A yields:

$$g_U = \frac{P - 3k_1}{2(\beta - k_2\varphi)} - \frac{k_1 + \alpha V'_U + (1 + k_2)\varphi + G}{2(\varphi^2 - \theta k_1)} \tag{13}$$

$$g_D = \frac{(1 - k_1)\alpha\varphi V'_U + \alpha V'_D + (P - \alpha - k_1\gamma)G + k_2}{\beta - k_2\varphi} \tag{14}$$

$$A = \frac{(P - k_1\gamma)\varphi + \alpha V'_D + \theta}{2\beta(\alpha - k_1\gamma)} + \frac{P - \alpha - k_2\gamma}{\beta - k_2\varphi} \tag{15}$$

Substitute A, g_U and g_D back into the Hamiltonian functions of Enterprise U and Enterprise D:

$$\begin{aligned} rV_D(G) = {} & \tfrac{\varphi\alpha V'_U + G + (\alpha+1)\varphi V'_D + \theta}{\alpha - k_1\gamma} + P\theta k_1[\varphi V'_U + V'_D + G]^2 - \beta G V'_D \\ & + [\beta k_1 + (1 - P)(\varphi - G)]\tfrac{(1-k_2)V'_U + \alpha\varphi V'_D}{2\beta(\alpha - k_1\gamma)(\beta - c_D)} \end{aligned} \tag{16}$$

$$rV_U(G) = \frac{\beta V'_U + (1 - k_1\gamma)\varphi + \alpha V'_D}{\alpha + P - k_1\gamma} + \frac{(P - \alpha k_1)V'_U}{\beta - k_2\varphi} + \frac{\alpha k_1 + (1 - P)\beta}{2(\varphi^2 - \theta k_1)} + \frac{(1 - \gamma)V'_U V'_D}{\beta(1 - P)(P - \alpha - k_1\gamma)} \tag{17}$$

Let: $V_D^{B*}(G) = m_1^B G^2 - m_2^B G + m_3^B$, $V_U^{B*}(G) = t_1^B G^2 - t_2^B G + t_3^B$.

Substituting into the Hamiltonian equations and solving by the undetermined coefficients method yields:

$$\begin{cases} m_1^B = \frac{P - k_1}{k_2(P - \alpha - k_1\gamma)} - \frac{\theta k_1 + (1 - k_1\gamma + k_2)\varphi}{2(\varphi^2 - \beta - k_2\varphi)} \\ m_2^B = \frac{(1-\gamma)\alpha + k_1\gamma}{\beta(1-P)(P - \alpha - k_1\gamma)} \\ m_3^B = \frac{(P - k_1\gamma)\varphi + 2\alpha\beta + \theta}{2\beta(\alpha - k_1\gamma + \varphi^2)} \\ t_1^B = \frac{\alpha\kappa_1 + (1 - k_1\gamma + k_2)\varphi}{2(\varphi^2 - \theta k_1)} + \frac{\varphi\alpha + (k_1\gamma + 1)\varphi + \theta}{\beta(1-P)(\varphi^2 - \beta)} \\ t_2^B = \frac{\beta + (1 - k_1\gamma)\varphi}{\alpha\varphi^2 - k_1\gamma} + \frac{P - \alpha k_1}{\beta} \\ t_3^B = 0 \end{cases} \tag{18}$$

Substituting back into A, g_U and g_D yields the optimal decision functions of Enterprise U and Enterprise D:

$$g_U = \frac{(1-k_2)k_1\gamma + \alpha\varphi}{2\beta(\alpha - k_1\gamma)(\beta - c_D)}e^{-rt} - \frac{k_1 + \alpha(P - \alpha k_1) + (1 + k_2)\varphi}{2(\varphi^2 - \theta k_1)} \tag{19}$$

$$g_D = \frac{(1-k_1)\alpha k_1\gamma + (P - \alpha - k_1\gamma)}{2(\varphi^2 - \theta k_1 - c_D)}e^{-rt} + \frac{(1 - k_1\gamma + k_2)\alpha - k_2\gamma}{\varphi^2 - \theta k_1} \tag{20}$$

$$A = \frac{(P - k_1\gamma)\varphi + \alpha(\theta k_1 - c_D) + \theta}{2\beta^2(\alpha - k_1\gamma)} + \frac{P - \alpha k_1}{\beta - k_2\varphi} - 2(\varphi^2 - \theta k_1) \tag{21}$$

The optimal value functions of Enterprise U and Enterprise D can be expressed as:

$$V_D(G) = \left[\frac{P - k_1}{k_2(P-\alpha-k_1\gamma)} - \frac{\theta k_1 + (1 - k_1\gamma + k_2)\varphi}{2(\varphi^2 - \beta - k_2\varphi)}\right]G^2 - \frac{(1-\gamma)\alpha + k_1\gamma}{\beta(1-P)(P-\alpha-k_1\gamma)}G + \frac{(P - k_1\gamma)\varphi + 2\alpha\beta + \theta}{2\beta(\alpha - k_1\gamma + \varphi^2)} \tag{22}$$

$$V_U(G) = [\frac{\alpha k_1 + (1 - k_1\gamma + k_2)\varphi}{2(\varphi^2 - \theta k_1)} + \frac{\varphi\alpha + (k_1\gamma + 1)\varphi + \theta}{\beta(1-P)(\varphi^2 - \beta)}]G^2 - [\frac{\beta + (1 - k_1\gamma)\varphi}{\alpha\varphi^2 - k_1\gamma} + \frac{P - \alpha k_1}{\beta}]G \tag{23}$$

The optimal trajectory of the green supply chain reputation is:

$$G(t) = [G_0 - \frac{\theta}{\delta}A]e^{-\delta t} + \frac{\theta}{\delta}A \tag{24}$$

Through the above process, the conclusion in Proposition 1 can be proved. □

3.2. Government Subsidy Model for Green Enterprises (Model S)

In the government subsidy model for green enterprises, the government provides a subsidy S to enterprises assessed as green factories and publicizes the list of green factories, i.e., providing cost-free promotion AG to green enterprises. The green perception of consumers for the upstream enterprise is $S_U^S(t) = k_1 g_U(t) A_G$. The objective functions of the two enterprises are:

$$\max_{g_U} \pi_U = \int_0^\infty e^{-rt}\{(P - C_U)Q_U + S\}dt \tag{25}$$

$$\max_{A, g_D} \pi_D = \int_0^\infty e^{-rt}\left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2\right\}dt \tag{26}$$

Proposition 2.

- The optimal greenness trajectory of the brown enterprise is $g_D^{S*} = \frac{(1-k_2)k_1 A_G\gamma + \alpha\varphi}{2\beta(\alpha - k_1 A_G\gamma)(\beta - c_d)}e^{-rt} - \frac{k_1 + \alpha(P - \alpha k_1 A_G) + (1 + k_2)\varphi}{2(\varphi^2 - \theta k_1 A_G)}$, the optimal greenness trajectory of the green enterprise is $g_D^{S*} = \frac{(1-k_1)\alpha k_1 A_G\gamma + (P - \alpha - k_1 A_G\gamma)}{2(\varphi^2 - \theta k_1 A_G - c_d)}e^{-rt} + \frac{(1 - k_1 A_G\gamma + k_2)\alpha - k_2\gamma}{\varphi^2 - \theta k_1 A_G}$;
- The degree of greenwashing by the brown enterprise is $A^{S*} = \frac{(P - k_1 A_G\gamma)\varphi + \alpha(\theta k_1 A_G - c_d) + \theta}{2\beta^2(\alpha - k_1 A_G\gamma)} + \frac{P - \alpha k_1 A_G}{\beta - k_2\varphi} - 2(\varphi^2 - \theta k_1 A_G)$;
- The optimal trajectory of the brand reputation of the brown enterprise is $G^{S*} = [G_0 - \frac{\theta}{\delta}A]e^{-\delta t} + \frac{\theta}{\delta}A$;
- The optimal profit value function of the green enterprise is $V_D^{S*}(G) = m_1^S G^2 - m_2^S G + m_3^S$, $V_U^{S*}(G) = t_1^S G^2 - t_2^S G + t_3^S$.

Proof 2. The Hamiltonian function of Enterprise D is:

$$rV_D(G) = \max_{A,g_D}\left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2 + V'_D(\theta A - \delta G)\right\} \tag{27}$$

Taking the partial derivatives of A and g_D, respectively, and setting them to 0 yields:

$$A = \frac{\theta V'_D - g_D k_2 \varphi(P - \alpha g_D + c_D g_D)}{\rho} \tag{28}$$

$$g_D(t) = \frac{G - A_G g_U k_1 \varphi}{2(\alpha - A k_2 \varphi)} + \frac{P}{2(\alpha - c_D)} \tag{29}$$

The Hamiltonian function of Enterprise U is:

$$rV_U(G) = \max_{g_U}\{(P - C_U)Q_U + S + V'_U(\theta A - \delta G)\} \tag{30}$$

Substituting the above two equations into the Hamiltonian function of Enterprise U, taking the partial derivative of g_U and setting it to 0 yields:

$$g_U(t) = \frac{P}{2c_U} - \frac{G + \gamma A\, g_D k_2}{2(\beta - A_G k_1 \gamma)} \tag{31}$$

Following the same steps as in Section 3.1, the optimal decision functions of Enterprise U and Enterprise D are:

$$g_U = \frac{(1-k_2)A_G k_1 \gamma + \alpha\varphi}{2\beta(\alpha - k_1 A_G \gamma)(\beta - c_D)} e^{-rt} - \frac{k_1 + \alpha(P - \alpha k_1 A_G) + (1 + k_2)\varphi}{2(\varphi^2 - \theta k_1 A_G)} \tag{32}$$

$$g_D = \frac{(1-k_1)\alpha A_G k_1 \gamma + (P - \alpha - A_G k_1 \gamma)}{2(\varphi^2 - \theta A_G k_1 - c_D)} e^{-rt} + \frac{(1 - A_G k_1 \gamma + k_2)\alpha - k_2 \gamma}{\varphi^2 - \theta k_1} \tag{33}$$

$$A = \frac{(P - A_G k_1 \gamma)\varphi + \alpha(\theta A_G k_1 - c_D) + \theta}{2\beta^2(\alpha - A_G k_1 \gamma)} + \frac{P - \alpha A_G k_1}{\beta - k_2 \varphi} - 2(\varphi^2 - \theta A_G k_1) \tag{34}$$

The optimal value functions of Enterprise U and Enterprise D can be expressed as:

$$\begin{cases} m_1^S = \frac{P - k_1 A_G}{k_2(P - \alpha - A_G k_1 \gamma)} - \frac{\theta A_G k_1 + (1 - A_G k_1 \gamma + k_2)\varphi}{2(\varphi^2 - \beta - k_2 \varphi)} \\ m_2^S = \frac{(1-\gamma)\alpha + k_1 \gamma}{\beta(1-P)(P - \alpha - k_1 \gamma)} \\ m_3^S = \frac{(P - A_G k_1 \gamma)\varphi + 2\alpha\beta + \theta}{2\beta(\alpha - A_G k_1 \gamma + \varphi^2)} \\ t_1^S = \frac{\alpha A_G k_1 + (1 - A_G k_1 \gamma + k_2)\varphi}{2(\varphi^2 - \theta A_G k_1)} + \frac{\varphi\alpha + (A_G k_1 \gamma + 1)\varphi + \theta}{\beta(1-P)(\varphi^2 - \beta)} \\ t_2^S = \frac{\beta + (1 - A_G k_1 \gamma)\varphi}{\alpha\varphi^2 - A_G k_1 \gamma} + \frac{P - A_G \alpha k_1}{\beta} \\ t_3^S = S \end{cases} \tag{35}$$

$$V_D(G) = \left[\frac{P - k_1 A_G}{k_2(P - \alpha - A_G k_1 \gamma)} - \frac{\theta A_G k_1 + (1 - A_G k_1 \gamma + k_2)\varphi}{2(\varphi^2 - \beta - k_2 \varphi)}\right] G^2 - \frac{(1-\gamma)\alpha + A_G k_1 \gamma}{\beta(1-P)(P - \alpha - A_G k_1 \gamma)} G + \frac{(P - A_G k_1 \gamma)\varphi + 2\alpha\beta + \theta}{2\beta(\alpha - A_G k_1 \gamma + \varphi^2)} \tag{36}$$

$$V_U(G) = [\frac{\alpha A_G k_1 + (1 - A_G k_1 \gamma + k_2)\varphi}{2(\varphi^2 - \theta A_G k_1)} + \frac{\varphi\alpha + (A_G k_1 \gamma + 1)\varphi + \theta}{\beta(1-P)(\varphi^2 - \beta)}] G^2 - [\frac{\beta + (1 - A_G k_1 \gamma)\varphi}{\alpha\varphi^2 - A_G k_1 \gamma} + \frac{P - A_G \alpha k_1}{\beta}] G + S \tag{37}$$

The optimal trajectory of the green supply chain reputation is:

$$G(t) = [G_0 - \frac{\theta}{\delta} A] e^{-\delta t} + \frac{\theta}{\delta} A \tag{38}$$

Through the above process, the conclusion in Proposition 2 can be proved. □

3.3. Government Regulation Model for Brown Enterprises (Model R)

In the government regulation model for brown enterprises, enterprises are legally required to disclose environmental information. The government as regulator randomly inspects brown enterprises with probability p, discloses any misconduct, and imposes fines C_p if greenwashing is found. In this stage, consumers' green perception of the brown enterprise's own brand is $S_D^R(t) = (1-p)k_2 g_D(t)A(t)$. The brand reputation dynamics for the brown enterprise D are $\dot{G}(t) = [\theta - p]A(t) - \delta G(t)$. The objective functions of the two enterprises are:

$$\max_{g_U} \pi_U = \int_0^\infty e^{-rt}\{(P - C_U)Q_U\}dt \tag{39}$$

$$\max_{A,g_D} \pi_D = \int_0^\infty e^{-rt}\left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2 - C_p\right\}dt \tag{40}$$

Proposition 3.

- The optimal greenness trajectory of the brown enterprise is $g_D^{R*} = \frac{(1-(1-p)\ k_2)k_1\gamma+\alpha\varphi}{2\beta(\alpha\ -\ k_1\gamma)(\beta\ -\ c_D)}e^{-rt}$ $-\frac{k_1+\alpha(P\ -\alpha k_1)+(1\ +\ (1-p)\ k_2)\varphi}{2(\varphi^2-[\theta-p]k_1)}$, the optimal greenness trajectory of the green enterprise is $g_D^{R*} = \frac{(1-k_1)\alpha k_1\gamma+(P-\alpha-k_1\gamma)}{2(\varphi^2-(\theta-p)k_1-c_D)}e^{-rt} + \frac{(1-\ k_1\gamma+(1-p)k_2)\alpha-(1-p)\ k_2\gamma}{\varphi^2-(\theta-p)k_1}$;
- The degree of greenwashing by the brown enterprise is $A^{R*} = \frac{(P-\ k_1\gamma)\varphi+\alpha((\theta-p)k_1-cd)+\theta-p}{2\beta^2(\alpha\ -\ k_1\gamma)} + \frac{P\ -\alpha k_1}{\beta-\ (1-p)\ k_2\varphi} - 2(\varphi^2 - (\theta-p)k_1)$;
- The optimal trajectory of the brand reputation of the brown enterprise is $G^{S*} = [G_0 - \frac{\theta-p}{\delta}A]e^{-\delta t} + \frac{\theta-p}{\delta}A$;
- The optimal profit value function of the green enterprise is $V_D^{R*}(G) = m_1^R G^2 - m_2^R G + m_3^R$, $V_U^{R*}(G) = t_1^R G^2 - t_2^R G + t_3^R$.

Proof 3. The Hamiltonian function of Enterprise D is:

$$rV_D(G) = \max_{A,g_D}\left\{(P_D - C_D - P)Q_D - \frac{1}{2}\rho A^2 - pC_p + V\prime_D(\theta A - \delta G)\right\} \tag{41}$$

Taking the partial derivatives of A and g_D in the above equation, respectively, and setting them to 0 yields:

$$A = \frac{[\theta - p]V'_D + g_D k2\varphi(p-1)(P - \alpha g_D + c_D g_D)}{\rho} \tag{42}$$

$$g_D(t) = \frac{G\ -\ g_U k_1\varphi}{2(\alpha\ -\ Ak_2\varphi(p-1))} + \frac{P}{2(\alpha\ -\ c_D)} \tag{43}$$

The Hamiltonian function of Enterprise U is:

$$rV_U(G) = \max_{g_U}\{(P - C_U)Q_U + V'_U((\theta - p)A - \delta G)\} \tag{44}$$

Substituting the above two equations into the Hamiltonian function of Enterprise U, taking the partial derivative of g_U and setting it to 0 yields:

$$g_U(t) = \frac{P}{2c_U} - \frac{G\ +\ (1-p)\gamma A\ g_D k_2}{2(\beta-\ k_1\gamma)} \tag{45}$$

Following the same steps as in Section 3.1, the optimal decision functions of Enterprise U and Enterprise D are:

$$g_U = \frac{(1-(1-p)\ k_2)k_1\gamma + \alpha\varphi}{2\beta(\alpha\ -\ k_1\gamma)(\beta\ -\ c_D)}e^{-rt} - \frac{k_1 + \alpha(P\ -\alpha k_1) + (1\ +\ (1-p)\ k_2)\varphi}{2(\varphi^2 - [\theta - p]k_1)} \tag{46}$$

$$g_D = \frac{(1-k_1)\alpha k_1\gamma + (P-\alpha - k_1\gamma)}{2(\varphi^2 - [\theta-p]k_1 - c_D)}e^{-rt} + \frac{(1-\ k_1\gamma + (1-p)k_2)\alpha - (1-p)\ k_2\gamma}{\varphi^2 - [\theta-p]k_1} \tag{47}$$

$$A = \frac{(P-\ k_1\gamma)\varphi + \alpha([\theta-p]k_1 - cd) + [\theta-p]}{2\beta^2(\alpha\ -\ k_1\gamma)} + \frac{P\ -\alpha k_1}{\beta -\ (1-p)\ k_2\varphi} - 2(\varphi^2 - [\theta-p]k_1) \tag{48}$$

The optimal value functions of Enterprise U and Enterprise D can be expressed as:

$$\begin{cases} m_1^R = \frac{P\ -k_1}{(1-p)\ k_2(P-\alpha-k_1\gamma)} - \frac{(\theta-p)k_1+(1-\ k_1\gamma+\ (1-p)k_2)\varphi}{2(\varphi^2-\beta-(1-p)\ k_2\varphi)} \\ m_2^R = \frac{(1-\gamma)\alpha+k_1\gamma}{\beta(1-P)(P-\alpha-k_1\gamma)} \\ m_3^R = \frac{(P-\ k_1\gamma)\varphi+2\alpha\beta+(\theta-p)}{2\beta(\alpha\ -\ k_1\gamma+\varphi^2)} - pC_p \\ t_1^R = \frac{\alpha k_1+(1-\ k_1\gamma+(1-p)\ k_2)\varphi}{2(\varphi^2-(\theta-p)k_1)} + \frac{\varphi\alpha+(k_1\gamma+1)\varphi+(\theta-p)}{\beta(1-P)(\varphi^2-\beta)} \\ t_2^R = \frac{\beta+(1-\ k_1\gamma)\varphi}{\alpha\varphi^2-\ k_1\gamma} + \frac{P\ -\alpha k_1}{\beta} \\ t_3^R = 0 \end{cases} \tag{49}$$

$$V_D(G) = \left[\frac{P\ -k_1}{(1-p)\ k_2(P-\alpha-k_1\gamma)} - \frac{(\theta-p)k_1+(1-\ k_1\gamma+\ (1-p)k_2)\varphi}{2(\varphi^2-\beta-(1-p)\ k_2\varphi)}\right]G^2 - \frac{(1-\gamma)\alpha+k_1\gamma}{\beta(1-P)(P-\alpha-k_1\gamma)}G + \frac{(P-\ k_1\gamma)\varphi+2\alpha\beta+(\theta-p)}{2\beta(\alpha\ -\ k_1\gamma+\varphi^2)} - pC_p \tag{50}$$

$$V_U(G) = [\frac{\alpha k_1 + (1-\ k_1\gamma + (1-p)\ k_2)\varphi}{2(\varphi^2 - (\theta-p)k_1)} + \frac{\varphi\alpha + (k_1\gamma+1)\varphi + (\theta-p)}{\beta(1-P)(\varphi^2-\beta)}]G^2 - [\frac{\beta + (1-\ k_1\gamma)\varphi}{\alpha\varphi^2 -\ k_1\gamma} + \frac{P\ -\alpha k_1}{\beta}]G \tag{51}$$

The optimal trajectory of the green supply chain reputation is:

$$G(t) = [G_0 - \frac{\theta - p(A)}{\delta}A]e^{-\delta t} + \frac{\theta - p(A)}{\delta}A \tag{52}$$

Through the above process, the conclusion in Proposition 3 can be proved. □

3.4. Model Comparison

This section compares the product greenness, degree of greenwashing by the brown enterprise, and total profits of enterprises under the three decision models, and obtains the following conclusions:

Corollary 1. Given $A_G \geq 1,\ p < 1$, the product greenness and degree of greenwashing by brown enterprises under the three models satisfy: $g_u^{2*}(t) > g_u^{3*}(t) > g_u^{1*}(t)$, $g_d^{3*}(t) > g_d^{2*}(t) > g_d^{1*}(t)$, $A^{2*} > A^{1*} > A^{3*}$. It follows that:

Under the benchmark model without government intervention, allowing the disruptive effects of greenwashing behaviors represents the worst state with the lowest greenness, and the degree of greenwashing chosen by the brown enterprise is highest to maximize profits. Under the government subsidy model, subsidies and publicity for green enterprises lead to higher greenness for the green enterprise compared to the benchmark model, but the greenness of the brown enterprise does not improve, and it increases greenwashing to compete with the green enterprise. Under the government regulation model without subsidies for green enterprises but with monitoring and penalties for brown enterprises, the greenness levels of both enterprises are higher than the benchmark model due to the positive impact of greenwashing costs, and the degree of greenwashing is lower due to the negative impact of costs.

Corollary 2. The total profit relationships under the three models are: When $C_p > \Delta_1$, $V_D^{1*}(t) > V_D^{2*}(t) > V_D^{3*}(t)$; When $C_p < \Delta_1$, $V_D^{1*}(t) > V_D^{3*}(t) > V_D^{2*}(t)$; When $S > \Delta_2$, $V_U^{1*}(t) < V_U^{2*}(t) < V_U^{3*}(t)$. $\Delta_1 = \frac{1}{p}[(m_1^R - m_1^S)G^2 + (m_2^S - m_2^R)G + \frac{(P - k_1\gamma)\varphi + 2\alpha\beta + (\theta - p)}{2\beta(\alpha - k_1\gamma + \varphi^2)} - m_3^S]$, $\Delta_2 = (t_1^R - t_1^S)G^2 + (t_2^S - t_2^R)G$.

For the brown enterprise, total profit under the subsidy model is lower than under the benchmark model. Total profit under the regulation model is also lower than under the benchmark when there is no penalty cost. When the penalty cost is zero, profit under regulation is higher than under the subsidy model. As the penalty cost increases, profit under regulation gradually decreases to the level of the subsidy model. In contrast, total profit for the green enterprise is higher under both the subsidy and regulation models compared to the benchmark. The critical value of profit under the subsidy model is mainly affected by the positive impact of subsidies: the greater the subsidy, the greater the total profit.

In a previous study, Sun [44] divided enterprises into advantaged and disadvantaged groups and developed two game models exploring the evolution of green cleaning and innovation strategies, considering government penalties and subsidies. Sun also analyzed the evolutionary stabilization strategies (ESSs) of the models and the evolution process for both enterprise groups. The study found that penalties effectively deterred "greenwashing" by both firm types, while subsidies did not inhibit disadvantaged enterprises.

This paper builds on previous research using a dynamic game model considering long-term enterprise operations. The model confirms earlier findings and provides insights into decision-making over time. Additionally, incorporating consumer perceptions of green products on demand offers valuable information for consumer-oriented policies.

4. Simulation and Analysis of Influencing Factors

Next, numerical simulations model the equilibrium results under different decision models to analyze the product greenness and optimal profit functions of enterprises. The parameter values are set as: $P = 0.8$, $\alpha = 0.8$, $\beta = 0.7$, $\kappa_1 = 0.3$, $\kappa_2 = 0.15$, $\varphi = 0.7$, $\gamma = 0.9$, $c_U = 0.7$, $c_D = 0.5$, $\theta = 0.6$, $\delta = 0.4$, $A_G = 1.5$, $\mathrm{p} = 0.5$.

4.1. Policy Comparison

According to the numerical simulation, the degree of greenwashing by the brown enterprise at each stage is:

$$\mathrm{A}^1 = 1.70,\ \mathrm{A}^2 = 2.10,\ \mathrm{A}^3 = 0.13$$

Based on $\mathrm{A}^3 < \mathrm{A}^1 < \mathrm{A}^2$, under carbon neutrality, effective punitive policies significantly reduce the degree of greenwashing by brown enterprises compared to subsidy policies and the free market, where brown enterprises expand greenwashing to compete for demand. The greenness levels of both enterprises follow the same ranking. For greenwashing governance, subsidy policies do not reduce greenwashing behaviors of brown enterprises, but rather cause greater greenwashing efforts. In contrast, government punitive mechanisms effectively reduce false promotions by brown enterprises, achieving the purpose of greenwashing governance.

The optimal trajectories of product greenness under the three models are shown in Figures 1–3, respectively. Initially, $g_D < g_U$ and, as time increases, g_U and g_D both decrease with the difference reducing. This shows that downstream greenwashing adversely affects upstream green enterprises. This leads to unhealthy market competition, eventually resulting in the lemon market problem.

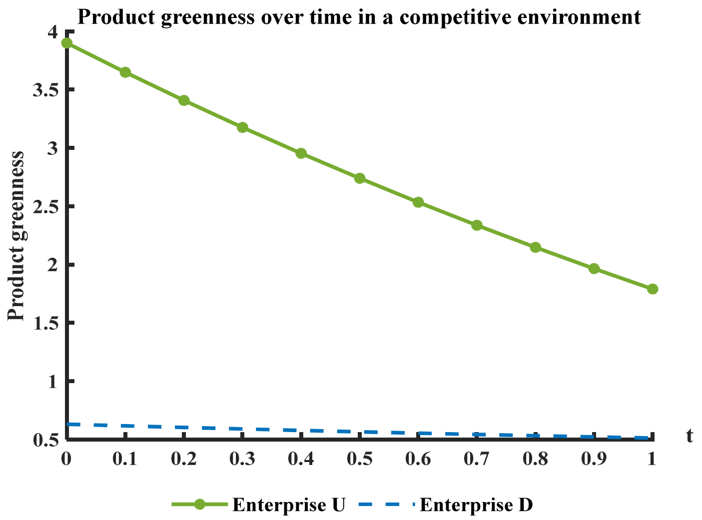

Figure 1. Optimal greenness trajectory under free competition model.

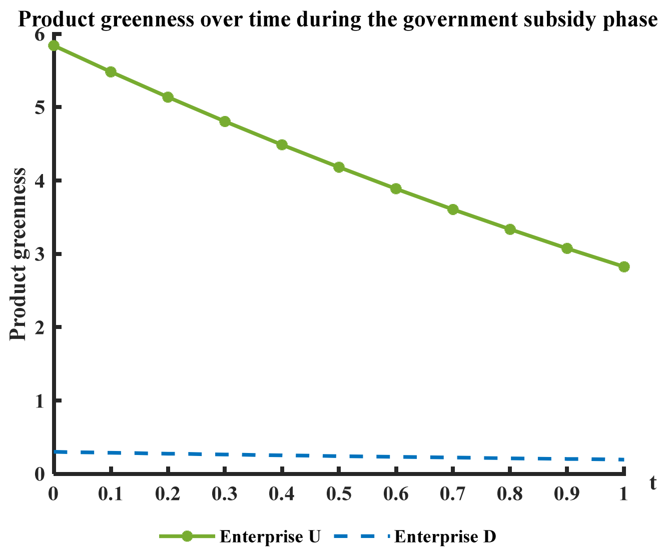

Figure 2. Optimal greenness trajectory under government subsidy model.

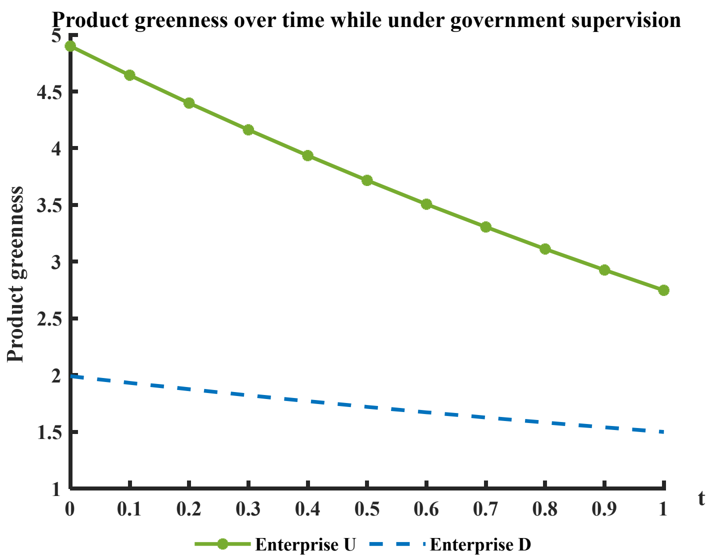

Figure 3. Optimal greenness trajectory under regulation model.

Figure 4 shows that as the government regulatory intensity increases, the degree of enterprise greenwashing gradually decreases. With the increase of government supervision, the degree of "greenwashing" of enterprises has gradually decreased. It can be seen that when the government conducts supervision, greenwashing enterprises will reduce their greenwashing behavior under the pressure of supervision, and when the government's perceived supervision is increased, enterprises will gradually choose not to greenwashing. It shows that government supervision is an effective means to control enterprise greenwashing behavior.

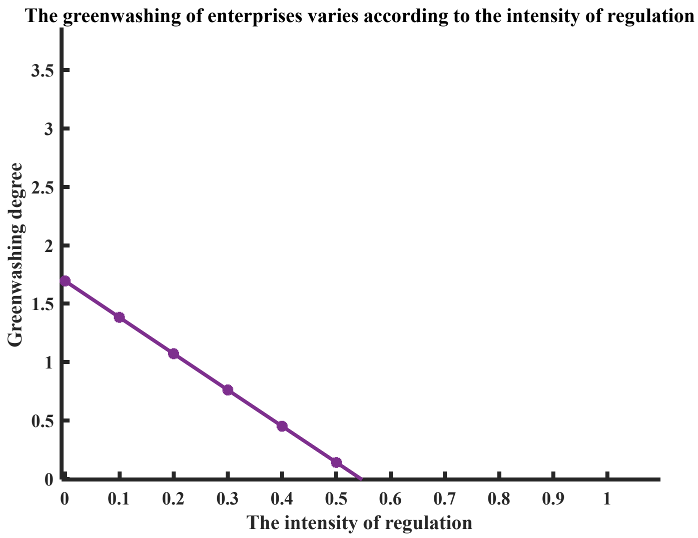

Figure 4. Impact of regulatory intensity on enterprise greenwashing under regulation model.

4.2. *The Impact of Consumer Green Perception on "Greenwashing"*

Under the government regulation scenario, Figure 5 shows the influence of consumers' perception coefficients for different enterprise types on the degree of greenwashing. The figure shows that when the consumers' perception coefficient for green enterprises is relatively small, brown enterprises engage in some greenwashing. As the perception coefficient for green enterprises increases, the degree of greenwashing by brown enterprises gradually decreases. When the consumers' perception coefficient for brown enterprises is relatively low, the degree of greenwashing is also small. As the perception coefficient for brown enterprises increases, the degree of greenwashing increases.

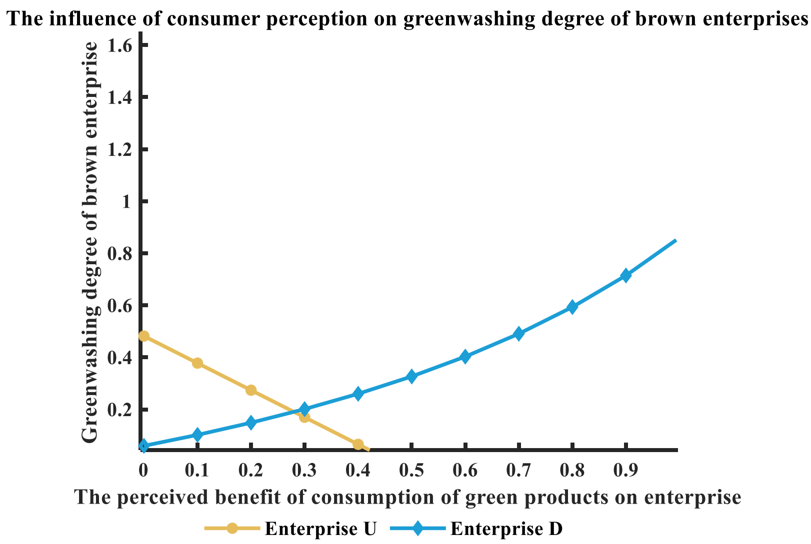

Figure 5. Impact of consumer green perception on greenwashing.

5. Conclusions and Policy Recommendations

A Stackelberg differential game model is established incorporating both green and brown enterprise types. The model compares greenness and total profits under two government scenarios: subsidies for green enterprises and regulation of brown enterprises. It further analyzes the mechanism behind brown enterprise greenwashing formation. Through a sensitivity analysis of the model parameters under different scenarios, the inhibitory effects of government policies on corporate greenwashing are investigated. The results show that: (1) Given the assumptions, when the government subsidizes green enterprises and regulates brown enterprises, compared to free market competition, green enterprises improve product greenness for higher profits, while the limited greenness improvement for regulated brown enterprises results in lower profits. (2) With government subsidies for only green enterprises, brown enterprises increase greenwashing to compensate for decreased total profits. Under government regulation, brown enterprises curb greenwashing behaviors. (3) In the regulatory model, the degree of brown enterprise greenwashing depends on the intensity of government oversight. As the regulatory intensity rises, this model outperforms the free competition model. Consumer green perception also affects brown enterprise greenwashing, with higher green enterprise perception coefficients reducing greenwashing, while higher brown enterprise perception coefficients increase greenwashing.

Based on the differential game analysis, policy recommendations for greenwashing governance include:

(1) Consider both the direct effects of policies targeting brown enterprises and indirect effects of green enterprise subsidies, such as appropriately reducing manufacturer subsidies to decrease fiscal burden and greenwashing.

(2) Use a combination of subsidies and regulation, as the model shows that joint deployment effectively improves supply chain greenness. Regulation can focus on monitoring green advertising and improving techniques, such as establishing a green advertising case law database and national real-time online monitoring system.

(3) Encourage consumer participation by sharing information and conducting joint anti-greenwashing activities through websites introducing green product knowledge. This can alleviate information asymmetry in the green product market, improve consumer perception of green enterprises, and strengthen awareness of greenwashing.

Author Contributions: H.Z.: Conceptualization, writing—original draft. Y.Z.: Methodology, data curation, writing—original draft. K.W.: Methodology, software, writing—review & editing. D.S.: Investigation, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Social Science Fund in China (no. 19BGL185), The Major Project of Philosophy and Social Science of Jiangsu Province (2023SJZD025), the Clean Energy Branch of Huaneng International Power Jiangsu Energy Development Co., LTD. [no. HN-49A0-202100016-PWQT00015; HN-49A0-202100016-PWQT00019], and the Ministry of Education Humanities and Social Sciences Fund (19YJC630138).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: I would like to thank Thomas A. Gavin, Cornell University, for his help in editing this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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