

# Entry Threshold Setting and Incentive Design for Green Order Financing

Jinzhao Shi, Kewen Jing, Xiaoping Xu, Li Zhou, Qiang Du, and T.C.E. Cheng

**Abstract**—In the green order financing (GOF), suppliers must first obtain “green certification” from core enterprises before they can secure bank financing to fulfill eco-friendly orders. In practice, core enterprises often face challenges in establishing green certification standards, particularly in setting a reasonable entry threshold for suppliers to access GOF. This paper examines the setting of entry threshold for GOF and proposes incentives to coordinate the GOF system. Specifically, we study a GOF system consisting of a bank, a large retailer, and a capital-constrained supplier. The retailer, acting on behalf of the bank, sets the greenness entry threshold for the supplier to access more preferential GOF, leveraging its informational advantages regarding the supplier’s environmental performance. We find that the supplier will opt for GOF only when the entry threshold set by the retailer is below a critical value; otherwise, it will continue using traditional order financing (TOF). In a Stackelberg game with the retailer as the leader, a unique equilibrium emerges between the two sides of the supply chain, under which GOF is implemented, leading to Pareto improvements and enhanced greenness. As another participant in the system, the bank also benefits from providing GOF, provided that it sets a reasonable interest rate—no lower than a certain threshold. If the bank’s GOF interest rate falls below this threshold, external government incentives will be necessary. We demonstrate that the government will only refrain from subsidizing the bank if the supplier’s cost coefficient of green investment is extremely high while the bank’s GOF interest rate is exceedingly low. Otherwise, the government will be willing to provide subsidies (transfer payments) to the bank, resulting in

Pareto improvements for all three GOF members and achieving greater social welfare than with TOF. Finally, we conduct numerical studies to validate the findings and extend the analysis to include a new formulation of consumer surplus, a new game sequence, a new subsidy category, and the retailer’s pricing decisions, further confirming the robustness of the results.

**Managerial Relevance Statement**—Our findings provide actionable insights for managers and policymakers in designing effective green certification mechanisms and targeted incentive strategies within the Green Order Financing (GOF) system. The results demonstrate that well-designed certification mechanisms not only enhance the economic and environmental performance of the supply chain, but also, when combined with targeted incentive strategies, can significantly boost overall social welfare within the GOF system. Engineering managers in core enterprises, particularly large retailers, can leverage these insights by setting appropriate greenness thresholds to strategically select suppliers and collaborating with banks to offer preferential order financing, thereby achieving dual improvements in both supply chain performance and sustainability. The study further emphasizes the importance of well-coordinated incentive strategies in expanding the operational capacity of the GOF. Policymakers can apply these insights by developing targeted subsidy schemes that compensate banks for extending preferential green financing, thereby ensuring their continued participation and enhancing the environmental impact of GOF. Moreover, by monitoring the cost-effectiveness of green investments across industries, policymakers can strategically direct subsidies toward projects that deliver tangible environmental benefits and create significant impact, maximizing their contribution to broader social welfare.

This paper also contributes to the following SDGs: SDG 8, SDG 12.

**Index Terms**—Green order financing, capital constraints, supplier financing, entry threshold setting, green certification, government incentives, Pareto improvement.

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Jinzhao Shi is with the School of Economics and Management, Chang’an University, Xi’an 710064, China, also with the Research Center on Green Engineering and Sustainable Development, Chang’an University, Xi’an 710064, China (e-mail: jzshi@chd.edu.cn).

Kewen Jing is with the School of Economics and Management, Chang’an University, Xi’an 710064, China, also with the Research Center on Green Engineering and Sustainable Development, Chang’an University, Xi’an 710064, China (e-mail: 2022123042@chd.edu.cn).

Xiaoping Xu is with the School of Business, Anhui University, Hefei 230601, China (e-mail: xpxu@ahu.edu.cn).

Li Zhou is with the Business School, University of Greenwich, London, SE10 9LS, UK (e-mail: zl14@gre.ac.uk).

Qiang Du is with the School of Economics and Management, Chang’an University, Xi’an 710064, China, also with the Research Center on Green Engineering and Sustainable Development, Chang’an University, Xi’an 710064, China (e-mail: q.du@chd.edu.cn).

T.C.E. Cheng is with the Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China (e-mail: edwin.cheng@polyu.edu.hk).

## I. INTRODUCTION

AS the global economy grows rapidly, high levels of carbon dioxide emissions are causing severe environmental issues, such as the greenhouse effect and extreme weather events, which present significant challenges to human production and daily life [1]. In response, many governments have set ambitious carbon reduction targets, such as the EU’s “Fit for 55” and China’s “3060 targets”. Since the carbon footprint of industries extends far beyond a company’s direct operations, effective decarbonization must encompass the entire supply chain [2], [3], [4]. According to a research report by the World

TABLE I  
PRACTICAL CASES OF GOF<sup>1</sup>

Case Name	Participants (Bank-Core Enterprise -Suppliers)	Implementation Mechanism	Green Supplier Certification Method
Sustainable Supply Chain Financing Plan	HSBC - Walmart - Suppliers	Suppliers that meet sustainability rating requirements can apply for preferential green financing from HSBC	Walmart Sustainability Index Program
Sustainable Supply Chain Financing Incentive Agreement	Santander Bank - Tesco - Suppliers	Suppliers can enjoy preferential financing rates on Santander Bank's supply chain financing platform after meeting a series of sustainability criteria	Tesco's sustainability criteria
Green Supply Chain Finance in the Greater Bay Area	Guangdong Green Finance Commission (GGFC) - Guangzhou Automobile Group Co., Ltd. (GAC) - Suppliers	Suppliers who meet the GAC's green supply chain management requirements can obtain preferential order-based loans from all banks under the governance of GGFC	GAC's green supplier evaluation system

Resources Institute (WRI), Scope 3 emissions—which include indirect emissions from raw materials and/or parts from suppliers—account for approximately 75% of the average carbon footprint of manufacturing firms [5]. This proportion is even higher for large retail companies, such as Walmart and Tesco [6]. In addition, consumer preference for green products is also increasing [1], [3], [7]. As a result, in response to environmental goals and growing consumer demand for green products, more core enterprises in supply chains have begun to implement green supply chain management to promote collaborative emissions reduction with their suppliers, such as Apple's "Supplier Clean Energy Project", Schneider Electric's "Supplier Zero Carbon Project", Ikea's "Suppliers Go Renewable", and Walmart's "Supplier Energy Efficiency Program" [8], [9].

However, most suppliers in supply chains are small and medium-sized enterprises (SMEs), and efforts to reduce emissions or implement green upgrades often place a financial strain on them [1], [10], [11]. In Southeast Asia, where SMEs are highly concentrated, over 40% of SMEs report that limited financial resources are their greatest obstacle to addressing climate change<sup>2</sup>. Additionally, according to a 2023 EU survey of 2142 enterprises across member states, SMEs face more significant constraints in terms of both funding and technical capabilities for green development compared with large enterprises<sup>3</sup>. Therefore, solving the two critical challenges of "financing" and "emission reduction" faced by small suppliers

has become an urgent global issue. Notably, the latest innovations in green supply chain finance, particularly Green Order Financing (GOF), offer a promising solution. Table I presents a few practical cases of GOF.

From Table I, unlike traditional order financing, where a core enterprise's order alone is sufficient for financing application, green order financing requires upstream small and medium-sized suppliers to not only obtain the core enterprise's endorsement but also meet specific green certification standards and ensure that the funds are exclusively used for green production. In other words, it is evident that "green certification" is a prerequisite for suppliers to participate in the GOF, which offers lower interest rates. The certification typically evaluates quantitative metrics such as carbon emission intensity and sustainability index, and it is generally managed by core enterprises within supply chains, leveraging their informational advantages in assessing suppliers' environmental performance, more effectively than banks<sup>4</sup>. However, *in practice, core enterprises face the challenge of establishing green certification standards, particularly in setting a reasonable entry threshold for suppliers to access the GOF*. Setting the threshold too high may require substantial green investments, deterring suppliers from participation, whereas setting it too low could hinder the growth of green products and markets. Furthermore, the effective operation of the GOF system also depends on the participation and incentives of banks and governments. As mentioned in Table I, HSBC offers preferential green financing to suppliers meeting Walmart's green certification standards, and Industrial Bank provides low-interest, order-based loans to upstream SMEs that satisfy GAC's green supply chain requirements, supported by local government subsidies for specialized green credit. In terms of government policy, many governments also incentivize bank participation in the GOF system through targeted subsidies and policy support to foster industrial green upgrading. Notable examples include Guangzhou and Guizhou, which provide direct financial incentives to financial institutions offering green credit services<sup>5</sup>.

Despite its practical importance, this challenge remains unsolved in existing GOF research. On one hand, prevailing research on GOF predominantly characterizes core enterprises as either credit guarantors [12], [13] [14] or trade financing providers [15], [16], [17], largely overlooking their pivotal role in green certification for financing green suppliers. On the other hand, most GOF studies tend to focus on the integrated decisions of suppliers regarding "financing" and "green upgrading" within various supply chain settings, such as mixed financing [18], channel competition [17], [19], and game power structures [20], whereas the coordination of the GOF system, aimed at achieving Pareto improvements and enhancing the green performance, remains a significant gap,

<sup>1</sup>The links in the table are as follows: <https://www.financeun.com/newsDetail/24206.shtml>; <https://www.toutiao.com/article/7020686413947732511/?wid=1749300466144>; <https://www.cnemission.com/article/jydt/scyj/202009/20200900001982.shtml>.

<sup>2</sup><https://www.ccpit.org/singapore/a/20220224/20220224xqme.html>

<sup>3</sup><https://finance.sina.com.cn/esg/2024-06-28/doc-incahznz4305797.shtml>

<sup>4</sup><https://www.cnemission.com/article/jydt/scyj/202009/20200900001982.shtml>

<sup>5</sup><https://finance.sina.com.cn/money/bank/yhpl/2023-03-22/doc-imymtmmw2839208.shtml>

especially in systems incorporating green certification mechanisms. Therefore, *this study examines the green certification mechanism (specifically, the setting of the greenness entry threshold by core enterprises for their suppliers' access to preferential green loans) within the GOF model, and proposes incentives for the GOF system (including banks, retailers, and suppliers) to achieve Pareto improvements in profits and enhance social value. To the best of our knowledge, this is the first study to address the entry threshold for suppliers' access to the GOF in the context of green supply chain finance.*

The main findings and contributions are summarized as follows. First, we characterize the green certification mechanism within the GOF system, where the large retailer (core enterprise) sets a greenness entry threshold for its capital-constrained supplier to access more preferential GOF. We find that the supplier will choose GOF only if the entry threshold set by the retailer is below a critical value; otherwise, it will continue to apply TOF (traditional order financing). In a Stackelberg game with the retailer as the leader, a unique equilibrium emerges between the two supply chain parties, under which GOF is implemented, leading to Pareto improvements and enhanced greenness. Our findings differ from those of previous studies without considering green certification, such as He et al. [20] and Liang & Zhang [21], which suggested that GOF can only achieve Pareto improvements under specific conditions. Second, we reveal that the bank, as another key participant in the system, also benefits from providing GOF, provided that it sets a reasonable interest rate—no lower than a certain threshold. If the bank's GOF interest rate falls below this threshold, external government incentives become necessary. We demonstrate that the government will only refrain from subsidizing the bank if the supplier's cost coefficient of green investment is extremely high while the bank's GOF interest rate is exceedingly low. Otherwise, the government will be willing to provide subsidies (transfer payments) to the bank, resulting in Pareto improvements for all three GOF participants and generating greater social welfare than with TOF. In contrast to Jin et al. [14], who thought that government subsidies to banks do not generate positive social welfare when the cost coefficient of green investment is high, our findings show that positive outcomes are still possible under such conditions, thereby expanding the current understanding. These internal and external coordination strategies of the GOF system under the green certification mechanism are highly original and have been overlooked in existing GOF literature [3], [20]. Finally, we extend the analysis to include a new formulation of consumer surplus, a new game sequence, a new subsidy category and the retailer's pricing decisions, further confirming the robustness of our results.

We organize the rest of the paper as follows: Section II reviews the relevant literature, while Section III introduces the research problem and discusses the key assumptions. Section IV examines the decisions in the TOF case, and Section V

analyzes the decisions and equilibrium outcomes in the GOF case. In Section VI, we explore the internal and external incentive issues of the GOF system and propose corresponding incentive schemes to achieve Pareto improvements. Section VII presents numerical studies to validate our findings and extends the analysis to include consumer surplus, a new game sequence, government subsidy, and the retailer's pricing decisions. Finally, Section VIII concludes the paper.

## II. LITERATURE REVIEW

This paper explores the green certification mechanism within the GOF system and its implications for GOF coordination, contributing to the emerging field of Green Supply Chain Finance (GSCF). In Section II.A, we begin by reviewing existing research on green certification in operation management field, examining the economic and environmental impacts of eco-labels, and identifying two key research gaps: the unexplored role of core enterprises in the supply chain and the insufficient attention given to the financial incentives behind green certification. In Section II.B, we provide a summary of recent studies on GSCF where GOF is included, which integrates the dual aspects of supply chain finance and green supply chain management. Then we highlight the innovations of this paper in comparison with existing GOF research, especially the green certification mechanism within the GOF system.

### A. Green Certification in Operations Management

At the early stage, many previous empirical research has confirmed the direct impact of green certifications on market demand and enterprise performance. Palacios-Argüello et al. [22] explored the effects of various environmental criteria on consumer demand within the French food industry, finding that organic certification of raw materials is the most influential factor in enhancing product environmental quality and stimulating demand growth. In a similar vein, Shalique et al. [23] studied the sustainable practices of suppliers in India from a behavioral perspective, showing that green certification can foster stakeholder trust, although the actual eco-behavior decisions of suppliers are influenced by their risk preferences. Yang et al. [24] argued that while green certification is crucial for corporate green development, it alone is insufficient to effectively promote the diffusion of green supply chain management during the preparation and development phases.

In the field of operations management, eco-labels are widely regarded as a representative green certification tool, primarily because of their ability to enhance stakeholder trust. Most research examines the effects of eco-labels on enterprise profits, environmental benefits, and social welfare across various contexts. The literature typically categorizes eco-labels based on the certifying authority into two types: internal self-labels and external national labels. Murail et al. [25] compared the effects of self-labels and external certifications on two competing firms with varying inherent credibility levels, finding that external certification improves the

environmental quality of both firms, with the less credible firm consistently opting for external certification. Gao et al. [26] demonstrated that stringent eco-label certification can increase both the supplier's profits and environmental benefits within a dual-channel supply chain, though profit growth for the manufacturer occurs only when the green investment cost coefficient is sufficiently low. Hou et al. [27] analyzed the optimal label selection strategies for competing firms and found that national labels generate greater social welfare, though at the cost of economic performance. In contrast, Xue et al. [28] concluded that while government eco-labels combined with green marketing can synergistically enhance product greenness, they do not necessarily improve either enterprise profits or overall social welfare. Notably, Nadar and Ertürk [29] compared eco-label designs in a duopoly market, showing the environmental benefits of multi-tier eco-labels under specific conditions. Given the information asymmetry in product greenness and environmental quality, researchers have also explored the information disclosure functions of eco-labels. Cao et al. [30] found that combining green label certification with wholesale pricing contracts can alleviate double marginalization and efficiency losses, while the certification mechanism enhances the transmission of green signals. Gao and Wei [31] compared the impacts of different environmental policies—eco-labels, green subsidies, and hybrid policies—on the individual firm's production decisions and social welfare, finding that eco-labels can effectively curb greenwashing and enhance social welfare.

Existing research on eco-label certification has primarily focused on label selection strategies and their economic/environmental impacts in single-firm decision-making scenarios [28], [30], [31] or duopoly competition scenarios [25], [27], [29]. These studies often consider governmental agencies, non-governmental organizations (NGOs), or firms themselves as certifying authorities, largely overlooking the role of core enterprises within supply chains in green certification. And the literature predominantly assumes that certifying authorities directly determine product greenness levels [27], [28], [31] or adopt external standards [26], [30], with limited attention given to how these should define appropriate threshold for eco-label certification. Moreover, while the existing research discusses the value of eco-labels in terms of demand enhancing [23], [25], [27], [28], [30], [31], green premiums [29]; and policy subsidies [26], it largely neglects the potential financial incentives of green certification, which are common in practice.

To address these research gaps, this paper investigates the "green certification" mechanism implemented by core supply chain enterprises (large retailers) within GOF system, where suppliers must obtain "green certification" from core enterprises before they can secure bank financing to fulfill eco-friendly orders. Compared with previous studies, we reveal several important findings in this GOF framework. First, we investigate the conditions for the supplier to choose GOF, which depends on the entry threshold set by the retailer. And then we demonstrate that when the retailer is the leader of

Stackelberg game, a unique equilibrium emerges between the two supply chain parties, under which GOF is implemented, leading to Pareto improvements and enhanced greenness. This contrasts with previous studies that typically argue green certification improves environmental impact or social welfare, often at the expense of corporate profits. For example, Hou et al. [27] found that national eco-labels enhance social welfare and reduce economic performance. Furthermore, the research examines incentive mechanisms that can enhance social welfare.

### *B. Green Certification in Operations Management*

Supply chain finance (SCF) involves financing tied to actual trade transactions within the supply chain, aiming to address the financial challenges faced by SMEs upstream and downstream [32], [33]. In the realm of operations and supply chain management, SCF is often linked to the capital-constrained newsvendor (CCNV) issue [34], [35], which explores the decision-making of retailers under financial constraints. Some research has also redirected the focus of financing issues within the CCNV problem towards upstream suppliers or manufacturers in the supply chain [36], [37], [38].

Recently, there has been a growing interest in incorporating green or low-carbon strategies into the CCNV problem, leading to the rise of green supply chain finance (GSCF) as a prominent area of study within operations and supply chain management [1], [39], [40], [41], [42]. GSCF blends elements of supply chain finance with low-carbon supply chain management, emphasizing the integration of financial and environmental considerations. Therefore, unlike the conventional CCNV problem, GSCF addresses factors such as enhancing product environmental performance and reducing carbon emissions [43], [44], [45], while also factoring in consumer preferences for green products [46], [47] and governmental low-carbon regulations [1], [17], [39], [40], [41], [48].

In terms of financing for downstream players within low-carbon supply chains, research typically focuses on two main types of supply chain structures: manufacturer-retailer (capital demander) and supplier-manufacturer (capital demander). First, for the retailer financing issues, Cao and Yu [48] pioneered research on the ordering and trade financing policies of the retailer under the carbon trading scheme. Wu et al. [46] examined how trade credit financing influences the efficiency of the supply chain, particularly for the capital-constrained retailer and its upstream manufacturer's pricing and carbon reduction strategies. Ma et al. [45] compared scenarios where the retailer receives financing from either a green manufacturer or a bank, concluding that financing provided by the manufacturer often yields better returns. Second, for the manufacturer financing issues, Cao and Yu [39] investigated the case where the manufacturer uses carbon emission right mortgage loans to make green production and found that such a financing mode could improve the profitability of the manufacturer, while Cao et al. [43] reported that trade credit financing, compared with bank credit, generally leads to greater output and improved supply chain

TABLE II  
COMPARISONS WITH RELATED GOF STUDIES

Literature	Supplier Capital Constraint	Supplier Green Upgrading	Government Incentives	Entry Threshold Setting	Green Certification
Qin et al. [18]	√	√			
Xu et al. [17]	√	√			
Xia et al. [19]	√	√			
He et al. [20]	√	√			
Shi et al. [1]	√	√			
Qin et al. [49]	√	√			
Huang et al. [3]	√	√	√		
Liang & Zhang [21]	√	√	√		
This paper	√	√	√	√	√

efficiency, regardless of whether the capital-constrained manufacturer invests in low-carbon initiatives. Xu and Fang [47] studied the carbon reduction and bank financing decisions of a financially-constrained manufacturer under supplier guarantee, while Zou et al. [44] argued that both output uncertainty and emissions reduction affect the choice of the manufacturer toward bank loans and trade credit. Jin et al. [14] investigated how government incentives, such as loan guarantees and interest subsidies, impact the green production decisions of the capital-constrained manufacturer, revealing that interest subsidies are more effective in promoting green investments.

In terms of financing for upstream players within low-carbon supply chains, the supply chain structure of “supplier/manufacturer (capital demander)-retailer” is generally considered. Qin et al. [18] demonstrated that for a manufacturer facing a high production cost, combining retailer advance payments with bank credit financing can enhance the overall benefits for all parties and encourage the manufacturer to reduce emissions. Qin et al. [49] further elucidated the dual role of blockchain technology in green manufacturer financing (i.e., enhancing carbon-reduction outputs while lowering loan interest rates) and demonstrated that adopting this technology can improve overall supply chain performance when the associated cost is moderate. Xia et al. [19] investigated how competition within the supply chain affects the manufacturer’s decisions regarding low-carbon production and financing, especially choices toward bank loans and the retailer’s advance payment, while Xu et al. [17] considered the situation where the manufacturer with financial constraints sells green products through a retail platform and revealed the impact of the “correlation coefficient between potential market size and price of carbon permits” on the manufacturer’s selection between platform financing and bank financing. Shi et al. [1] found that procurement commitment contract provided by the larger retailer can improve bank credit access and production

capacity for the supplier with financial constraints, thereby increasing both economic and environmental outcomes for the entire supply chain. The findings of He et al. [20] further demonstrated that when the manufacturer’s carbon-reduction performance is closely linked to the bank loan interest rate, the GSCF system comprising the bank, retailer, and manufacturer may achieve superior economic and environmental performance under certain conditions. Notably, this performance is significantly enhanced under the bank-led power structure compared with the retailer-led scenario. With respect to government incentives for GSCF systems, Liang & Zhang [21] revealed that the consumption subsidies fail to enhance the supplier’s green investment level, but variations in subsidy rates significantly influence its choices between ESG equity financing and green credit financing. Huang et al. [3] further compared the performance of different governmental subsidy schemes for the manufacturer who obtains financing to make green investments, and pointed out that when the subsidy amount is equal, subsidizing the bank has greater advantages in terms of the product green level and overall social welfare than does subsidizing the supply chain members.

As demonstrated above, financing upstream green suppliers in supply chains—commonly referred to as Green Order Financing (GOF)—has been extensively studied, as summarized in Table II. It is evident that most GOF research, within the context of “financing green suppliers,” focuses on the integrated decisions of suppliers regarding both “financing” and “green upgrading” (i.e., enhancing product greenness or reducing carbon emissions) across various supply chain settings. These include mixed financing [18], channel competition [17], [19], game power structures [20], supply chain contracts [1], and blockchain applications [49], among others. A few studies also explore “government incentives” for GOF systems, such as consumption subsidies [21] and comparisons between subsidizing banks versus supply chain members [3].

However, these studies overlook a crucial role that core enterprises play in the GOF model beyond credit enhancement for suppliers: certifying the green qualifications of suppliers, which is a prerequisite for suppliers to implement GOF, as illustrated in Section I. Therefore, this paper focuses on the “green certification” mechanism within the GOF system and its implications for GOF coordination, areas that remain unexplored in existing literature. Our analysis reveals several key insights. First, we find that when the retailer is the leader of Stackelberg game, a unique equilibrium emerges between the two supply chain parties, under which GOF is implemented, leading to Pareto improvements and enhanced greenness. This outcome contrasts with situations where “green certification” is not considered, as green credit can only achieve similar results if the bank’s preferential pricing meets specific conditions [20]. Furthermore, we demonstrate that appropriate bank interest rate, combined with greenness entry threshold, can increase profits for all three GOF participants—the supplier, the retailer, and the bank, an

TABLE III  
SUMMARY OF THE NOTATION

Notation	Definition
$c$	Unit production cost of the product
$w$	Unit wholesale price of the product
$p$ (Decision variable in extended Section VII.E)	Unit selling price of the product
$R$	Loan interest rate under TOF provided by the bank
$r$	Loan interest rate under GOF provided by the bank
$\bar{e}$ (Decision variable)	Greenness entry threshold for supplier's GOF set by the retailer
$e$ (Decision variable)	Actual product greenness chosen by the supplier
$e_0^*$	Optimal product greenness of the supplier under TOF
$e^*$	Optimal product greenness of the supplier under GOF
$\tilde{e}$	A critical greenness entry threshold set by the retailer for supplier's undifferentiated financing between GOF and TOF
$a$	Intercept of the market demand, measuring the capacity of the market
$d$	Market demand, which is price- and greenness dependent, i.e., $d = a - p + e$
$k$	Cost coefficient of supplier's green investment
$\pi_X^Y$	Profits of the participants under different financing modes, where $X = S, R, B$ represents the supplier, retailer, and bank, respectively, while $Y = TOF, GOF$ denotes the case of TOF and GOF, respectively.
$CS$	Consumer surplus
$EI$	Environmental improvement
$SW$	Social welfare
$r^*, \underline{r}, r^{**}, r', r'_{CS}$	A group of thresholds of $r$ to divide various scenarios
$\hat{k}, \hat{k}_{CS}$	A group of thresholds of $k$ to divide various scenarios

internal incentive that has been overlooked in existing studies [20], [21], [49]. Lastly, we identify the effective range for government subsidy, demonstrating that its ability to improve social welfare depends on the combined effect of green investment cost coefficient and bank interest rate, differing from prior conclusions [3], [14], [21].

### III. PROBLEM DESCRIPTION AND ASSUMPTIONS

We examine a GOF system involving a bank, a large retailer, and a supplier with limited capital. The supplier manufactures a single kind of product at unit cost  $c$ , sells it to the retailer at wholesale price  $w$ , and the retailer then offers it to the end market at retail price  $p$ . Suppose that the wholesale and retail markets for the product are in equilibrium, so both  $w$  and  $p$  are exogenously given [1], [50], [51], [52]<sup>6</sup>. The market demand is price- and greenness dependent, i.e.,  $d = a - p + e$ , where  $a$  is the market capacity and  $e$  is the product greenness of the supplier<sup>7</sup>. Upgrading the product's

greenness incurs an additional cost  $ke^2/2$ , modeled as a quadratic function representing the increasing marginal cost of green investment or upgrading, which aligns with established research [1], [3], [14], [57].

The supplier, lacking internal capital [34], [14], [43], must seek external funding from the bank to finance its production and green investment/upgrading. To encourage sustainable development in the supply chain, the bank provides two financing options. One is TOF (traditional order financing), under which the supplier obtains financing at an interest rate  $R$  based on the order. The other is GOF (green order financing), which involves the retailer, on behalf of the bank, to establish a greenness entry threshold  $\bar{e}$ . If the supplier meets or exceeds this greenness threshold, it can access GOF at a lower interest rate  $r$ ; if not, only TOF is available. Fig. 1 shows a diagram of the TOF and GOF operations.

We answer the following questions: 1) How should the supplier decide between GOF and TOF when both options are available, and how can the retailer establish the appropriate entry threshold for the supplier's access to GOF? 2) What equilibrium arises between the supplier and retailer, and does GOF offer additional economic and environmental value to the supply chain? 3) Can the bank benefit from offering GOF rather than TOF, and under what conditions? In the case that GOF is not advantageous for the bank, how can the government design subsidies to incentivize the bank from the perspective of social welfare optimization? 4) How robust are the results when the analysis is extended to include consumer surplus, a new game sequence, and the retailer's pricing

<sup>6</sup>Such settings allow us to introduce a new and novel decision variable, i.e., the greenness entry threshold which will be introduced shortly. Similar settings on the wholesale and retail prices can be found in studies by Shi et al. [1], Lai et al. [51], Qin et al. [52], and others. In Section VII.E, we further incorporated the retailer's pricing decision and validated the robustness of the main findings of this paper.

<sup>7</sup>In this study, the coefficients of  $p$  and  $e$  are unified to 1, which helps to enhance the clarity and focus of the study, and avoids trivial conclusions. A similar approach can be found in studies by Chen et al. [53], Li et al. [54], Wu et al. [55], Ma et al. [56], and others. Research findings remain valid under asymmetric sensitivity coefficients, and the corresponding proofs are provided in Appendix D.

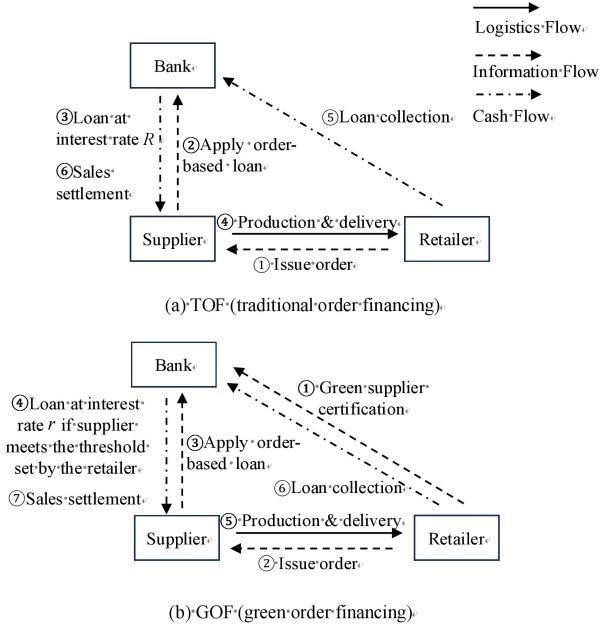


Fig. 1. Diagrams of TOF and GOF

decisions? To address the above issues, we model a Stackelberg game where the retailer leads, and the supplier follows. We identify the equilibrium strategy for both parties and highlight the significant benefits of GOF in boosting both economic and environmental outcomes. Additionally, we analyze how government incentives can effectively encourage the bank to provide GOF, and propose subsidy schemes that improve profits for all GOF participants (the bank, retailer, and supplier) and increase social welfare beyond what TOF offers. We also extend the problem to consider a new formulation of consumer surplus, a new game sequence between the GOF members, and the retailer's pricing decisions, further confirming the robustness of the results.

To solve these problems, we adopt several key assumptions. For clarity and ease of reference, we provide a summary of the primary notation used in this study in Table III.

**Assumption A1.**  $a > p > w > c(1+R)$ , where  $a > p$  ensures positive market demand, while  $p > w > c(1+R)$  is the basic participation constraint for the retailer and supplier [3], [43], [44].

**Assumption A2.**  $0 < r < R$ , which implies that the loan interest rate for GOF is lower than that for TOF. This aligns with common practice, as banks typically offer reduced interest rates to incentivize borrowers to opt for green financing options [14], [40], [49].

**Assumption A3.** When the participants, i.e., the supplier, retailer, bank, and government, are indifferent to choosing between GOF and TOF, they always choose GOF for green development concerns [3], [20].

#### IV. TRADITIONAL ORDER FINANCING CASE

In the TOF case, the supplier can only obtain financing from the bank at interest rate  $R$  based on orders for

production and delivery. As the retailer does not need to set the greenness entry threshold for the supplier, the supplier is the only decision maker that needs to choose a suitable level of product greenness  $e$  to maximize its profit as follows<sup>8</sup>:

$$\text{Max} \pi_S^{\text{TOF}}(e) = wd - \underbrace{(cd + ke^2/2)}_{\Delta} (1+R). \quad (1)$$

In (1),  $d = a - p + e$  is the market demand, " $\Delta$ " refers to the supplier's costs (production cost and greenness investment cost) under TOF. The supplier obtains a bank loan of  $\Delta$  for production and green investment. Following delivery, the retailer submits the full order payment  $wd$  to the bank. After that, the bank deducts the full loan amount plus interest, and then transfers the remaining balance to the supplier [3], [20]. Solving (1), we derive Proposition 1.

**Proposition 1.** In the TOF case,

(a) the optimal product greenness of the supplier is

$$e_0^* = \frac{w - c(1+R)}{k(1+R)}; \quad (2)$$

(b) the optimal profits of the supplier and retailer are  $\pi_S^{\text{TOF}}(e_0^*)$  and  $\pi_R^{\text{TOF}}(e_0^*) = (p - w) \cdot d(e_0^*)$ .

From the expression of  $e_0^*$  in (2), we find that  $de_0^*/dR < 0$ , implying that a decrease in the loan interest rate can stimulate the supplier's greenness performance. This leaves room for introducing "green finance" into the system, which we discuss below.

#### V. GREEN ORDER FINANCING CASE

##### A. Supplier's Problem

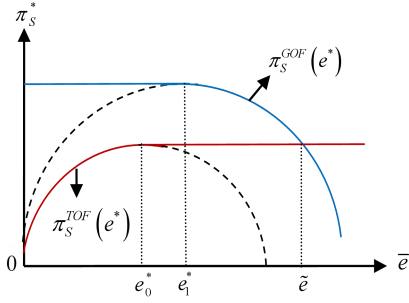
In the GOF case, the retailer sets an entry threshold for the supplier's green financing, i.e., setting a greenness threshold  $\bar{e}$ . If the supplier chooses the product greenness  $e$  that satisfies  $e \geq \bar{e}$ , it can obtain "green certification" from the retailer, on the basis of which it can obtain financing from the bank at a preferential loan interest rate  $r$  ( $r < R$ ). Of course, the supplier reserves the right to apply for traditional order financing (TOF) when it sets the product greenness  $e$  to meet  $e < \bar{e}$  after balancing the revenues and costs. Therefore, the key problem is, when GOF is available, how should the supplier choose between GOF and TOF, and what are the supplier's optimal greenness decisions? To solve this problem, we first study the supplier's optimal greenness decisions, under a given entry threshold  $\bar{e}$ , as follows:

$$\begin{cases} \text{Max} \pi_S^{\text{GOF}}(e | \bar{e}) = wd - \left( cd + \frac{1}{2} ke^2 \right) (1+r) \\ \text{s.t. } e \geq \bar{e} \end{cases} \quad \psi \quad (3)$$

$$\begin{cases} \text{Max} \pi_S^{\text{TOF}}(e | \bar{e}) = wd - \left( cd + \frac{1}{2} ke^2 \right) (1+R) \\ \text{s.t. } e < \bar{e} \end{cases} \quad \omega$$

<sup>8</sup>From (1), it is clear that  $\pi_S^{\text{TOF}}(e=0) = [w - c(1+R)](a - p) > 0$  and  $d\pi_S^{\text{TOF}}/de(e=0) = w - c(1+R) > 0$ , based on Assumption A1. Thus, the supplier will always choose to set a positive greenness to earn a positive profit, then bankruptcy will never occur if the supplier's decision is well-optimized.

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**Fig. 2.** Diagram of the supplier's optimal profit curves under GOF and TOF

In (3), problems “ $\Psi$ ” and “ $\Omega$ ” are the supplier's greenness optimization problems under GOF and TOF, respectively. Solving the problems, we obtain Proposition 2.

**Proposition 2.** *In the GOF case,*

(a) *if the supplier applies for GOF, its optimal product greenness  $e^*$  should be as follows:*

$$\begin{cases} e^* = e_1^* & \text{if } \bar{e} \leq e_1^* \\ e^* = \bar{e} & \text{if } \bar{e} > e_1^* \end{cases}; \quad (4)$$

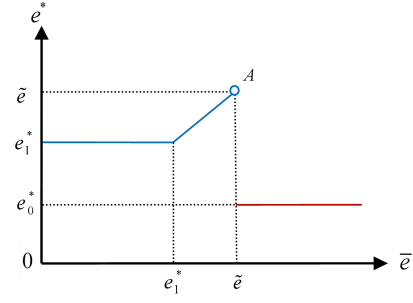
(b) *if the supplier applies for TOF, its optimal product greenness  $e^*$  should be as follows:*

$$\begin{cases} e^* = e_0^* & \text{if } \bar{e} > e_0^* \\ e^* \rightarrow \bar{e}^- & \text{if } \bar{e} \leq e_0^* \end{cases}. \quad (5)$$

where  $e_1^* = \frac{w-c(1+r)}{k(1+r)}$  and  $e_0^*$  follows (2).

From Proposition 2, the supplier's optimal greenness decision depends on the entry threshold for GOF set by the retailer, regardless of whether it applies for GOF or TOF. The two objective functions in (3), i.e.,  $\pi_s^{GOF}$  and  $\pi_s^{TOF}$ , are both quadratic functions whose axes of asymmetry are  $e_1^*$  and  $e_0^*$ , respectively, and  $e_1^* > e_0^*$  because  $r < R$ . Besides, it is obvious that for any given  $e$ ,  $\pi_s^{GOF}(e) \geq \pi_s^{TOF}(e)$ , implying that the curve of  $\pi_s^{GOF}$  is above that of  $\pi_s^{TOF}$ . However, when the constraints in (3) are considered, the supplier's optimal greenness decision becomes piecewise-defined under both GOF and TOF, as do the supplier's optimal profit curves. Fig. 2 shows a diagram of the supplier's optimal profit curves relative to the entry threshold  $\bar{e}$  under GOF and TOF, where the BLUE LINE describes the supplier's optimal profit curve when it applies for GOF, whereas the RED LINE shows that when it applies for TOF. We then obtain the following proposition concerning the supplier's optimal choice between GOF and TOF.

**Proposition 3.** *In the GOF case (when GOF is available), if the entry threshold for GOF set by the retailer satisfies  $\bar{e} \leq \tilde{e}$ , the supplier should set the product greenness above (or equal to)  $\bar{e}$  and apply for GOF; otherwise, i.e.,  $\bar{e} > \tilde{e}$ , it should set the product greenness below  $\bar{e}$  and apply for TOF.  $\tilde{e}$  is uniquely determined by*



**Fig. 3.** Diagram of the supplier's optimal greenness decision

$$\begin{cases} \pi_s^{GOF}(\tilde{e}) = \pi_s^{TOF}(e_0^*) \\ \text{s.t. } \tilde{e} > e_1^* \end{cases}. \quad (6)$$

Proposition 3 directly shows that if the entry threshold for GOF set by the retailer is not too high (lower than  $\tilde{e}$ ), the supplier would like to meet the greenness requirement and apply for GOF; otherwise, if the entry threshold is set too high (higher than  $\tilde{e}$ ), the increased marginal cost of the green investment makes GOF impractical, leading the supplier to choose TOF. Then, we analyze the supplier's optimal greenness decision. As shown in Fig. 2, for  $\bar{e} \in [0, e_1^*]$ , GOF (BLUE LINE) outperforms TOF, under which scenario the supplier sets  $e^* = e_1^*$ , as the first case in (4) shows; for  $\bar{e} \in (e_1^*, \tilde{e}]$ , GOF still outperforms, the supplier sets  $e^* = \bar{e}$ , as the second case in (4) describes; finally for  $\bar{e} \in (\tilde{e}, +\infty)$ , TOF (RED LINE) outperforms, the supplier sets  $e^* = e_0^*$ , as the first case in (5) answers. Fig. 3 further shows a diagram of the supplier's optimal greenness decision, and we obtain Proposition 4.

**Proposition 4.** *In the GOF case (when GOF is available), the optimal product greenness decision of the supplier is as follows:*

$$\begin{cases} e^* = e_1^* & \text{if } \bar{e} \in [0, e_1^*] \\ e^* = \bar{e} & \text{if } \bar{e} \in (e_1^*, \tilde{e}] \\ e^* = e_0^* & \text{if } \bar{e} \in (\tilde{e}, +\infty) \end{cases}. \quad (7)$$

From Fig. 3 and Proposition 4, it is clear that the supplier's optimal product greenness decision depends on the greenness entry threshold set by the retailer for the supplier's access to the GOF, which means that the supplier's choice for GOF (green certification) is ultimately determined by the retailer's threshold-setting. It challenges prior studies [27] which demonstrated that firms will not voluntarily adopt government eco-labels absent mandatory policy interventions. This difference arises because [27] attributes the value of eco-labels solely to their ability to build consumer trust, whereas our study shows that directly linking green certification to economic benefits, such as GOF at a lower interest rate, can effectively drive voluntary adoption. Furthermore, the supplier's optimal decision is not continuous with respect to such a threshold. Given the truth that  $e_1^* > e_0^*$ , the supplier's

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optimal greenness will reach its maximum when the retailer's threshold is set exactly at  $\bar{e}$ . This facilitates further research into the optimal decision of the retailer acting as the leader.

### B. Retailer's Problem

As the leader in the game, the retailer can set the entry threshold for GOF  $\bar{e}$  by manipulating the supplier's optimal greenness response as indicated in (7). Thus, the retailer's decision-making problem is as follows:

$$\text{Max}\pi_r^{\text{GOF}}(\bar{e} | e^*) = (p - w) \cdot d(e^*), \quad (8)$$

where  $d(e^*) = a - p + e^*$  represents the market demand under the supplier's best greenness response. By addressing this problem, we derive Proposition 5.

**Proposition 5.** *In the GOF case (when GOF is available), the retailer always chooses to set the entry threshold  $\bar{e}$  at*

$$\bar{e} = \tilde{e}. \quad (9)$$

Proposition 5 implies that the intention of the retailer is to stimulate the supplier's product greenness to its upper limit, which can bring the maximum benefit to the retailer. Therefore, the retailer chooses to set  $\bar{e} = \tilde{e}$ , at which the supplier's greenness response would be  $e^* = \tilde{e}$  on the basis of (7), reaching its upper limit as Point A in Fig. 3 fully displays.

### C. Equilibrium of the Game

Through the above analyses, in the GOF case (when GOF is available), if the entry threshold for GOF set by the retailer is not too high, i.e.,  $\bar{e} \leq \tilde{e}$ , the supplier would like to apply for GOF, and its optimal profit would be no less than that under TOF ( $\pi_s^{\text{TOF}}(e_0^*)$ ), as Fig. 2 shows; otherwise, if the entry threshold is set too high, i.e.,  $\bar{e} > \tilde{e}$ , the supplier would choose a conservative greenness  $e_0^*$  to earn the optimal profit under TOF. Overall, the optimal profit of the supplier in the GOF case (Section V) would be no less than that in the TOF case (Section IV). In addition, the supplier's optimal greenness level would also be superior to that under TOF, as shown in Fig. 3, which results in additional benefits for the retailer due to increased demand for green products. Therefore, introducing GOF leads to improved outcomes for both parties. However, as the Stackelberg game leader, the retailer would always set the entry threshold for GOF at  $\bar{e} = \tilde{e}$ , as described in Proposition 5, resulting in a unique game equilibrium.

**Proposition 6.** *In the GOF case (when GOF is available),*

(a) *the optimal profits of the supplier and retailer would be no less than those under TOF, implying that the introduction of GOF can lead to Pareto improvements in the profits of both parties;*

(b) *the unique equilibrium of the game with the retailer as the Stackelberg leader is  $\bar{e} = e^* = \tilde{e}$ .*

In the unique equilibrium described in Proposition 6, the supplier's optimal profit in the case of GOF is identical to that in the case of TOF, as exactly described in (6). Therefore, the supplier is indifferent to applying for GOF and will always choose it based on Assumption A3. However, an increase in the product's greenness level benefits the retailer, as it leads to

a higher sales volume. In other words, the retailer enjoys the advantages of the GOF mechanism independently, without negatively impacting the interests of the supplier. Consequently, GOF undeniably provides Pareto improvements in both parties' profits compared with TOF, and also enhance product greenness. This outcome contrasts with the results in scenarios where the "green certification" consideration is absent, where green credit can achieve similar performance only if the bank's preferential pricing meets specific conditions [20]. The effectiveness of the "interest rates linked to carbon reduction" mechanism in [20] is limited by the exogenous initial interest rate. In contrast, this study demonstrates that the green entry threshold set by the core retailer consistently achieves dual improvements in both economic and environmental performance, without relying on the design of complex financial instruments. The managerial implication is that when the "green certification" mechanism is introduced within the GOF system, both supply chain members (core enterprises and their suppliers) should be confident in adopting GOF, as long as both parties adhere to the decisions outlined in Proposition 6(b). This has been widely observed in practice.

## VI. INCENTIVES FOR THE GOF SYSTEM

### A. Internal Incentives within the GOF System

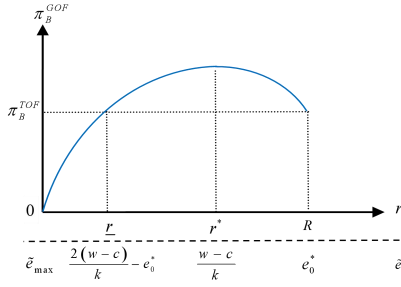
The analyses in Section V show that GOF can lead to Pareto improvements in the profits of both supply chain members. In this section, we are interested in whether the financial provider, i.e., the bank, has the motivation to provide GOF. In other words, whether and under what conditions could GOF benefit the bank as well? To answer this question, we first derive the bank's profit functions under TOF and GOF as follows:

$$\begin{cases} \pi_B^{\text{TOF}} = \left( cd + \frac{1}{2} ke^2 \right) R & \text{where } e = e_0^* \\ \pi_B^{\text{GOF}} = \left( cd + \frac{1}{2} ke^2 \right) r & \text{where } e = \tilde{e} \end{cases}. \quad (10)$$

In (10), the loan interest rate under TOF ( $R$ ) is usually fixed, so  $e_0^*$  and  $\pi_B^{\text{TOF}}$  can be viewed as constants. However, under GOF, a preferential loan interest rate is provided, i.e.,  $r < R$ , so the equilibrium greenness  $\tilde{e}$  would change accordingly, as the following shows.

**Proposition 7.** *In the GOF case, the equilibrium greenness of the product is negatively correlated with the preferential loan interest rate, i.e.,  $d\tilde{e}/dr < 0$ .*

Proposition 7 shows a negative correlation between  $\tilde{e}$  and  $r$  (a similar negative correlation between the level of product greenness/carbon reduction and the bank's interest rate has also been confirmed in previous POF studies, such as in [18], [19]). With the help of Fig. 2, we see that when  $r$  drops from  $R$  to zero,  $\tilde{e}$  will rise from  $e_0^*$  to  $\tilde{e}_{\max}$ , where  $\tilde{e}_{\max}$  is the larger root of  $\pi_s^{\text{GOF}}(\tilde{e}_{\max}; r=0) = \pi_s^{\text{TOF}}(e_0^*)$ . Furthermore, the increase in  $\tilde{e}$  will lead to an increase in the financing amount, i.e.,



**Fig. 4.** Diagram of the bank's profit curve under GOF

$cd + ke^2/2$ . Therefore, it is not possible to directly determine the size relationship between  $\pi_B^{GOF}$  and  $\pi_B^{TOF}$ . Fortunately, the results in Proposition 7 allow us to further discuss the variation in  $\pi_B^{GOF}$  with respect to  $r$ , which can help us find the scenario and boundary conditions where  $\pi_B^{GOF}$  outperforms  $\pi_B^{TOF}$ , as Proposition 8 summarizes.

**Proposition 8.** *In the GOF case,*

(a) *there exists a unique  $r^* \in (0, R)$ , such that when  $r \in (0, r^*)$ ,  $d\pi_B^{GOF}/dr > 0$ ; when  $r \in (r^*, R)$ ,  $d\pi_B^{GOF}/dr < 0$ ;*

(b) *there exists a unique  $\underline{r} \in (0, r^*)$ , such that when  $r \in [\underline{r}, R)$ ,  $\pi_B^{GOF} \geq \pi_B^{TOF}$ ;*

*where  $r^*$  and  $\underline{r}$  solve  $\pi_S^{GOF}(r^*; \tilde{e} = (w-c)/k) = \pi_S^{TOF}(e_0^*)$  and  $\pi_S^{GOF}(\underline{r}; \tilde{e} = [2(w-c)/k] - e_0^*) = \pi_S^{TOF}(e_0^*)$ .*

Proposition 8(a) implies that under GOF, the bank's profit  $\pi_B^{GOF}$  is unimodal to the preferential loan interest rate  $r$  set by itself. Fig. 4 shows a diagram of the bank's profit curve. When  $r$  drops from  $R$  to zero,  $\pi_B^{GOF}$  will first increase from  $\pi_B^{TOF}$  to its maximum value  $\pi_B^{GOF}(r^*)$ , and then gradually decreases to zero. It is clear that there is a unique  $\underline{r} \in (0, r^*)$ , and when  $r$  satisfies  $\underline{r} \leq r < R$ , we have  $\pi_B^{GOF} \geq \pi_B^{TOF}$ , as Proposition 8(b) describes. From the proof of Proposition 8, the one-to-one  $\tilde{e}$  under  $r^*$  and  $\underline{r}$  can be determined as  $\tilde{e}(r^*) = (w-c)/k$  and  $\tilde{e}(\underline{r}) = [2(w-c)/k] - e_0^*$ , respectively. Furthermore, it is not difficult to confirm that  $\tilde{e}_{\max} > [2(w-c)/k] - e_0^* > (w-c)/k > e_0^*$ , which supports the fact that  $0 < \underline{r} < r^* < R$ , in line with the results in Proposition 7.

In summary, Proposition 8 implies that as long as the bank sets a relatively high preferential loan interest rate (higher than  $\underline{r}$ ), it will gain greater benefits from participating in GOF than TOF. Combined with the results in Section V on the profit changes of the retailer and supplier, we obtain the following proposition.

**Proposition 9.** *In the GOF case, an internal incentive contract implemented by the bank and the retailer, i.e.,  $[r, \tilde{e}]$ ,*

*which meets  $\begin{cases} r \in [\underline{r}, R) \\ \tilde{e} = \tilde{e}(r) \end{cases}$ , can lead to Pareto improvements for all three GOF members, thus coordinating the GOF system.*

Proposition 9 suggests that when the bank's preferential loan interest rate is not excessively low (higher than  $\underline{r}$ ), GOF will lead to Pareto improvements for all participants under the mechanism of the greenness entry threshold set by the retailer. Such inside-GOF-system incentives, implemented through loan pricing and greenness-related regulations, have been overlooked in existing GOF studies such as [3], [20]. This suggests that, in practice, the well-structured decisions made by banks and retailers—acting as “financial service providers” and “core enterprises in the supply chain”—are crucial to the effective functioning of GOF. Banks should ensure that the preferential GOF interest rate remains above a certain threshold and allow retailers to establish the greenness entry threshold for suppliers' access to GOF accordingly. Thus, banks should balance incentives with profitability when determining interest rate strategies. However, to greatly stimulate industrial green development, the bank may offer an exceptionally attractive GOF loan interest rate ( $r < \underline{r}$ ). In this scenario, it becomes essential to introduce external government incentives into the GOF system, which we discuss further below.

### B. External Incentives by the Government

For the case of  $r < \underline{r}$ , the bank's profit under GOF is below that under TOF, so it has no motivation to participate in GOF unless supported by external incentives (such as government subsidies) [58]. Although the bank's profit is hurt in such a case, the low interest rate  $r$  can continuously stimulate the product greenness  $\tilde{e}$  to grow as Proposition 7 suggests, which undoubtedly brings extra benefits for the retailer, external environment, and others. Therefore, from the view of the government concerning overall social welfare, the performance of GOF may continue to improve in the case of  $r < \underline{r}$ , which gives the government a reason to provide subsidies to encourage the bank to join. So, the key problem is whether and under what conditions the government should provide subsidies to the bank, from the perspective of improving social welfare. Following [3], we define the social welfare without subsidy as

$$SW = \pi_S + \pi_R + \pi_B + CS + EI, \quad (11)$$

where the first three terms are the profits of the supplier, retailer, and bank, respectively, while  $CS$  and  $EI$  denote the consumer surplus and environmental improvement, respectively. Then, the social welfare under TOF can be written as  $SW^{TOF} = \pi_S^{TOF} + \pi_R^{TOF} + \pi_B^{TOF} + CS^{TOF} + EI^{TOF}$ , while that under GOF as  $SW^{GOF} = \pi_S^{GOF} + \pi_R^{GOF} + \pi_B^{GOF} + CS^{GOF} + EI^{GOF}$ . Furthermore, since  $\pi_S^{GOF} = \pi_S^{TOF}$  under the unique GOF equilibrium in Proposition 6(b), while  $CS^{GOF}$  and  $CS^{TOF}$  can be viewed as the same because the selling price of the product

> TEM-25-0813 <

is exogenously given [59], [60]<sup>9</sup>, we simplify the difference in social welfare under GOF and TOF as

$$\Delta SW = SW^{GOF} - SW^{TOF} = \Delta \pi_R + \Delta \pi_B + \Delta EI. \quad (12)$$

In (12),  $\Delta \pi_R = \pi_R^{GOF} - \pi_R^{TOF} = (p - w)(\tilde{e} - e_0^*)$ . From (A.6-7) in the proof of Proposition 8, we have  $\Delta \pi_B = \pi_B^{GOF} - \pi_B^{TOF} = (\tilde{e} - e_0^*)(w - c - k(\tilde{e} + e_0^*)/2)$ . Besides,  $EI$  is conventionally depicted as the environmental quality of green products, and it is linearly and positively correlated with the total greenness of products, i.e.,  $EI = \xi ed$  [61], [62]. For convenience,  $\xi = 1$  is often assumed, so  $EI$  is measured directly by the total greenness of products [3], [63], on the basis of which we formulate  $\Delta EI = EI^{GOF} - EI^{TOF} = (\tilde{e} - e_0^*)(a - p + \tilde{e} + e_0^*)$ . Then, we express  $\Delta SW$  in (12) as

$$\Delta SW = (\tilde{e} - e_0^*)[a - c + (1 - k/2)(\tilde{e} + e_0^*)]. \quad (13)$$

To facilitate the solving of the subsidy problem, we first clarify several properties of  $\Delta SW$  on the global domain of  $r$ , i.e.,  $r \in (0, R)$ , as summarized below.

**Proposition 10.** Regarding the properties of  $\Delta SW$ , we have

(a) when  $k \leq 2$ ,  $d\Delta SW/dr < 0$  over  $r \in (0, R)$ ;

(b) when  $k > 2$ , there exists a unique  $r^* \in (0, r^*)$  such that  $d\Delta SW/dr > 0$  over  $r \in (0, r^*)$ , while  $d\Delta SW/dr < 0$  over  $r \in (r^*, R)$ ;

(c)  $\Delta SW(r \rightarrow R) = 0$  and  $\Delta SW(r = \underline{r}) > 0$ ;

where  $r^*$  and  $\underline{r}$  follow those in Proposition 8, and  $r^*$  solves  $\pi_S^{GOF}(r^*; \tilde{e} = (a - c)/(k - 2)) = \pi_S^{TOF}(e_0^*)$ .

Propositions 10(a) and 10(b) indicate that the shape of  $\Delta SW$  depends strongly on  $k$ , i.e., the cost coefficient of green investment. When  $k \leq 2$ ,  $\Delta SW$  monotonically decreases with  $r$ ; when  $k > 2$ ,  $\Delta SW$  is unimodal in  $r$ . In both cases,  $\Delta SW > 0$  is likely to occur over  $r \in (0, \underline{r})$ , due to the realities in Proposition 10(c). This implies that within the domain where the bank refuses to participate in GOF, the overall social welfare under GOF still has the possibility of being greater than that under TOF, which gives the government an incentive to subsidize the bank to join. As long as the subsidy amount is not less than  $\underline{s} = \Delta r \cdot L(r) = (\underline{r} - r)[cd(r) + k\tilde{e}(r)^2/2]$ , the bank will undoubtedly return to GOF<sup>10</sup>. In fact, this subsidy is a post-incentive (transfer payment from the government to the bank) and does not change the level of the

<sup>9</sup>In classical economics, a change in the sales price of a product brings about a change in  $CS$ . However, the ‘‘psychological price (willingness to pay)’’ of consumers may change due to the rise of product greenness, which may also have an impact on  $CS$ . In Section VII.B we explore improvement of the  $CS$  formulation.

<sup>10</sup> $\Delta r$  is the subsidy rate, while  $L(r)$  is the actual loan volume. When  $s \geq \underline{s}$ , the bank’s profit under subsidy will be  $\pi_B^{GOF} + s \geq \pi_B^{GOF} + \underline{s} = rL(r) + \underline{s} = rL(r) \geq rL(\underline{r}) = \pi_B^{TOF}(r = \underline{r}) = \pi_B^{TOF}$ , thus it returns to GOF.

social welfare<sup>11</sup>. Thus, in the case of  $r \in (0, \underline{r})$ , the condition for the government to provide the subsidy is that the social welfare under GOF is no less than that under TOF, i.e.,  $\Delta SW \geq 0$ <sup>12</sup>. On the basis of Proposition 10, we further explore the conditions for generating  $\Delta SW \geq 0$  and propose the corresponding incentive schemes, as summarized in Proposition 11.

**Proposition 11.** For the case of  $r \in (0, \underline{r})$ , there exists a unique  $\hat{k} > 2$  such that

(a) when  $k \leq \hat{k}$ ,  $\Delta SW > 0$  always holds over  $r \in (0, \underline{r})$ , then the government will choose to subsidize  $s$  to the bank, and a

portfolio contract  $[r, \bar{e}, s]$  that meets 
$$\begin{cases} r \in (0, \underline{r}) \\ \bar{e} = \tilde{e}(r) \\ s = (\underline{r} - r)L(r) \end{cases} \text{ can}$$

incentivize all the participants to join GOF and produce higher social welfare than that under TOF<sup>13</sup>;

(b) when  $k > \hat{k}$ , there exists a unique  $r' \in (0, \underline{r})$  such that for  $r \in [r', \underline{r})$ ,  $\Delta SW \geq 0$  holds, then the government will follow the strategies in part (a) to subsidize; for  $r \in (0, r')$ ,  $\Delta SW < 0$ , then the government will not subsidize and the system turns to TOF;

where  $\hat{k}$  solves  $a - c + (1 - k/2)[\tilde{e}_{\max}(k) + e_0^*(k)] = 0$ , in which  $\tilde{e}_{\max}(k)$  is the maximum greenness and can be solved by  $\pi_S^{GOF}(\tilde{e}_{\max}; r = 0) = \pi_S^{TOF}(e_0^*)$ ; and  $r'$  solves  $\pi_S^{GOF}(r', \tilde{e} = [2(a - c)/(k - 2)] - e_0^*) = \pi_S^{TOF}(e_0^*)$ .

Proposition 11 indicates that in the case of  $r \in (0, \underline{r})$ , where the bank has no self-motivation to participate in GOF, the social welfare level under GOF may still outperform that under TOF, i.e.,  $\Delta SW > 0$ , under which scenario the government would like to subsidize the bank to join GOF. From the results in the proposition, we know that whether or not the government provides the subsidy depends on the supplier’s cost coefficient of green investment  $k$  and the bank’s loan interest rate under GOF  $r$ . When  $k$  is below the threshold  $\hat{k}$ , the government will have no hesitation in providing the subsidy; otherwise, it provides the subsidy only when  $r$  is above the threshold  $r'$ . In other words, when and only when  $k$  is relatively high, while  $r$  is extremely low, the government will not subsidize, under which scenario the supplier’s green investment becomes less cost-effective, and

<sup>11</sup>When the post-subsidy is introduced, the social welfare under GOF can be expressed as  $SW^{GOF} = \pi_S^{GOF} + \pi_R^{GOF} + (\pi_B^{GOF} + s) + CS^{GOF} + EI^{GOF} - s$ , remaining the same level as that without subsidy.

<sup>12</sup>For the case  $\Delta SW = 0$ , it is indifferent for the government to choose GOF and TOF. Based on Assumption A3, the government always chooses GOF.

<sup>13</sup>The range of subsidy rate could be  $\Delta r \in [\underline{r} - r, R - r]$ . However, a higher subsidy rate will not increase the level of social welfare (it will only increase the government’s transfer payments to the bank), so in our proposed strategy, the government provides the lowest subsidy level.

the driving effect of the bank's low interest rate on the supplier's green investment will be greatly weakened. Then, the bank's profit from GOF will sharply decline, which cannot be offset by the limited profit growth of the retailer and environment externality; thus, the overall social welfare will fall to a level below that under TOF, making the subsidy under GOF infeasible and meaningless. Therefore, Proposition 11 exactly outlines the conditions under which the government should subsidize banks and the corresponding incentive schemes to achieve Pareto improvements in the GOF system. This approach is not addressed in existing GOF incentive studies, which typically focus on the effects of different government subsidies on GOF decisions in basic scenarios without a "green certification" mechanism [3], [21].

Proposition 11 suggests that the government could subsidize banks to continuously lower the preferential GOF interest rate, which could still lead to Pareto improvements for the profits of all GOF members and produce higher social welfare. These subsidies can be implemented in most cases, except when both suppliers' green investment cost efficiencies and banks' preferential GOF interest rates are extremely low. Furthermore, the portfolio contract proposed in Proposition 11 offers a reference for the government and GOF members to operationalize GOF activities and achieve a win-win outcome.

## VII. NUMERICAL STUDIES AND EXTENSIONS

### A. Numerical Studies

In this subsection we conduct numerical studies to verify the main analytical findings obtained above. In light of the previous studies [3], [51], [52], we assume that  $p=10$ ,  $w=5$ ,  $c=2$ ,  $R=k=0.1$ , and  $a=50$ . We first verify the supplier's decision. Suppose that GOF is available and the preferential loan interest rate is  $r=0.05$ . When observing the GOF entry threshold given by the retailer, i.e.,  $\bar{e}$ , the supplier can either choose to set the product greenness to meet the threshold and then obtain GOF, or choose not to meet the threshold and still use TOF. According to the supplier's optimal decision rules obtained in Proposition 2, we can draw its expected profit curves under TOF and GOF, as shown in Fig. 5. It is clear that there is a critical value  $\tilde{e} \approx 40.27$  such that if  $\bar{e}$  is not greater than  $\tilde{e}$ , the supplier will choose GOF; otherwise, it will choose TOF, which is consistent with the conclusions in Proposition 3. This means that the supplier only chooses GOF when the GOF entry threshold set by the retailer is relatively low, since a high GOF entry threshold (greater than  $\tilde{e}$ ) will make the supplier's green investment uneconomical and turn the supplier to TOF.

Under the above optimal financing choices of the supplier, its corresponding optimal product greenness decision is shown in Fig. 6, which aligns with the findings presented in Proposition 4. It is clear that when GOF is available, the product greenness of the supplier will be no lower than that under TOF, which will also bring additional benefits to the retailer by driving the market demand of consumers with green preferences. Fig. 7 shows the profit changes of both the

retailer and supplier before and after introducing GOF. Obviously, for the cases where the supplier prefers to choose GOF, i.e.,  $\bar{e} \leq \tilde{e}$ , the retailer's profit will also be enhanced, i.e., the profits of both parties will achieve Pareto improvement, as shown in Proposition 6(a). However, as the leader of the game, the retailer will choose the decision that is most favorable to itself, i.e.,  $\bar{e} = \tilde{e}$ , at which point the system reaches the unique equilibrium, i.e.,  $\bar{e} = e^* = \tilde{e}$ , as shown in Propositions 5 and 6(b). In this equilibrium, the profits of the retailer and supplier are Pareto improved, and at the same time, the product greenness reaches its highest level.

Given that GOF can lead to Pareto improvements for both sides of the supply chain, we then look at whether the other participant in the system, i.e., the bank, has an incentive to provide GOF. In fact, the bank's expected profit under GOF is affected by the preferential loan interest rate  $r$  that it sets. As shown in Fig. 8, when  $r$  gradually decreases from  $R=0.1$ , the equilibrium product greenness of the system, i.e.,  $\tilde{e}$ , will monotonically increase, and the coupling effect of  $r$  and  $\tilde{e}$  determines the increase and decrease in the bank's profit. In this example, as  $r$  decreases, the bank's profit will first increase to its maximum value (when  $r^* \approx 0.093$ ) and then gradually decrease to zero. At the same time, there is another critical value  $\underline{r} \approx 0.078$ , when the bank's interest rate  $r$  is set at a level higher than  $\underline{r}$ , it will get extra benefit from GOF; otherwise, its profit will be lower than that under TOF, so losing its motivation to provide GOF. The above results fully verify the conclusions in Propositions 7 and 8.

Furthermore, as shown in Fig. 9, it is clear that in the interval where the bank has an internal motivation to participate, i.e.,  $[\underline{r} \approx 0.078, R=0.1)$ , the incentive contracts within the GOF system that are implemented by the bank and retailer, i.e.,  $\begin{cases} r \in [\underline{r}, R) \\ \bar{e} = \tilde{e}(r) \end{cases}$ , can bring Pareto improvements for all three GOF members, compared with TOF. Then, the conclusions in Proposition 9 are verified.

When the bank's preferential loan interest rate is set too low, i.e.,  $r < \underline{r}$ , it has no motivation to participate in GOF. At this point, the external government incentives are needed, and whether the government provides subsidy incentives (transfer payments to the bank) depends on whether the overall level of social welfare under GOF surpasses that under TOF. Fig. 10 shows the changes in  $\Delta SW$  (the difference in social welfare between GOF and TOF) at different values of  $k$  (the supplier's green investment cost coefficient). It is clear that when  $k$  is very small ( $k < 2$ ),  $\Delta SW$  monotonically increases as the bank's loan interest rate  $r$  decreases. In our example,  $\Delta SW$  grows very fast and is almost vertical. However, when  $k > 2$ ,  $\Delta SW$  becomes unimodal with  $r$ , i.e., as  $r$  decreases, it will first increase and then decrease. Furthermore, there exists a critical value  $\hat{k} \approx 515.4$  such that  $\Delta SW$  will always be positive when  $k$  is less than or equal to  $\hat{k}$ ; however, when  $k$  is greater than  $\hat{k}$ , whether or not  $\Delta SW$  is positive depends on

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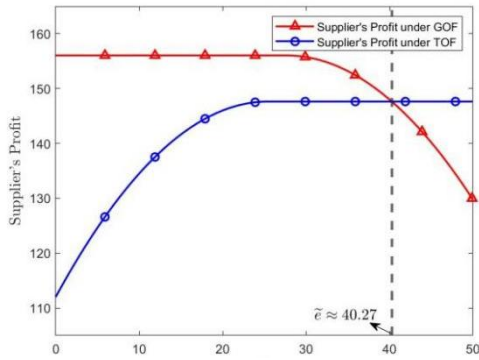


Fig. 5. Supplier profit curves under TOF and GOF

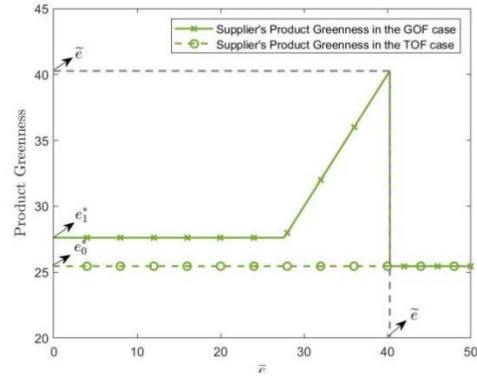


Fig. 6. Supplier's product greenness in the TOF and GOF cases

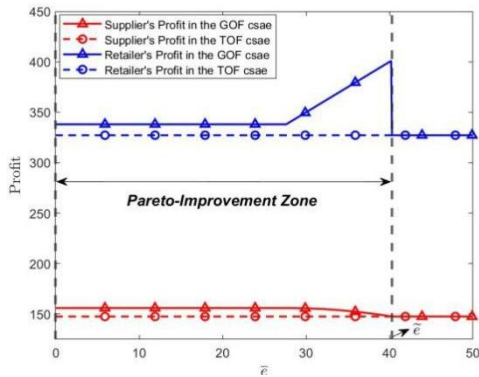


Fig. 7. Profit changes of supply chain members before and after introducing GOF

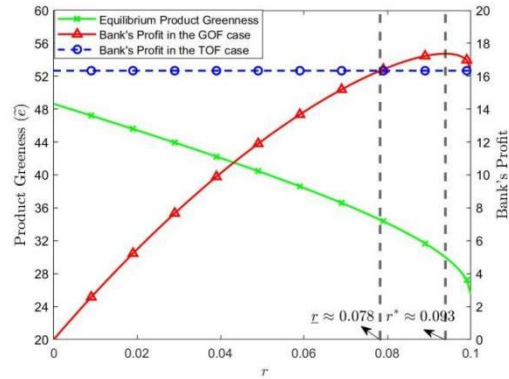


Fig. 8. Changes in equilibrium greenness and bank profit with  $r$  varying

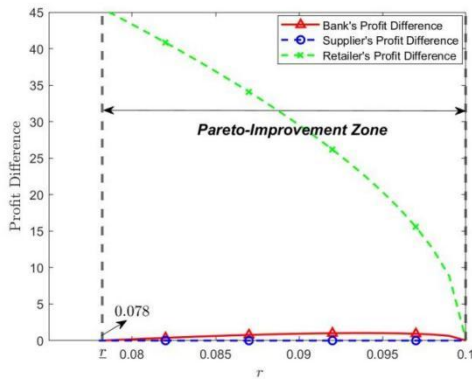


Fig. 9. Pareto improvement of the GOF system under internal incentive contracts

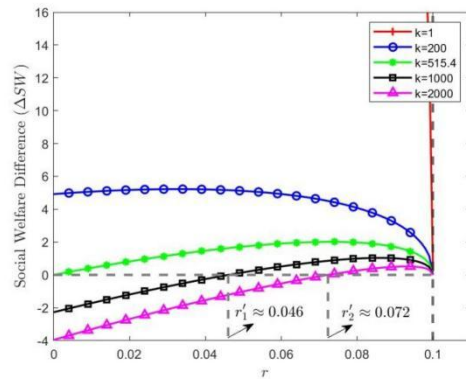
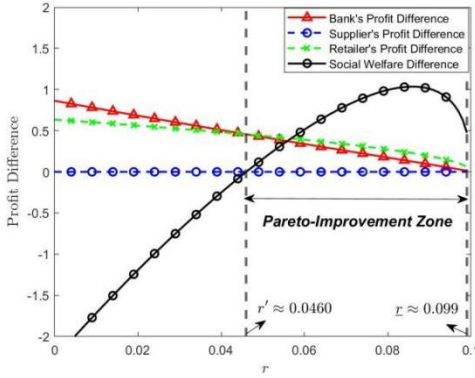


Fig. 10. Changes in  $\Delta SW$  with  $r$  varying at different  $k$  values

the setting of  $r$ . Taking  $k = 1000$  as an example, there exists a critical value  $r' \approx 0.046$  such that  $\Delta SW$  is positive when the bank's interest rate  $r$  is higher than  $r'$ ; otherwise, it is negative.

As shown in Fig. 11, in the interval where  $\Delta SW$  is positive, the government will be motivated to provide the bank with the transfer payment subsidy  $s$  in Proposition 11, which will make the profits of all three participants Pareto-improved compared with that under TOF, which of course means that the bank will return to GOF even if under the scenarios where it has no self-motivation to participant (the cases with  $r < r' \approx 0.099$  in this example). The numerical results in Fig. 10 and Fig. 11 verify the correctness and effectiveness of the

external government incentives given in Propositions 10 and 11. Furthermore, Fig. 10 also reveals the impact of the supplier's green investment cost coefficient on the social welfare difference. An increase in the coefficient indicates greater difficulty for enterprises in green upgrading, thereby weakening the relative advantage of GOF in enhancing overall system social welfare. This suggests that reducing the green investment cost coefficient for enterprises can effectively enhance the advantage of GOF.



**Fig. 11.** Pareto improvement of the GOF system under government subsidies ( $k = 1000$ )

### B. Extension for Considering Consumer Surplus

In classical economics, it is generally recognized that changes in product price bring about changes in consumer surplus (CS). Following [59] and [60], we did not consider CS in Section VI when formulating the social welfare of a low-carbon supply chain system, because the selling price of the product is exogenously given. As stated in Footnote 7, when consumers in the market have green awareness/preference, even if the selling price is fixed, the “psychological price (willingness to pay)” of consumers may change as product greenness changes, which may also change CS. Below, we reconsider the formulation of CS and give the corresponding adjustments of the government’s incentives.

Market demand is usually characterized as a function of price in classical economics, i.e.,  $D = a - bP$ . We depict the inverse demand function curve in Fig. 12(a). When the price is set at  $P^*$ , the equilibrium demand is  $D^*$ , implying that a total of  $D^*$  consumers will buy the product. For each consumer uniformly distributed between 0 and  $D^*$ , the CS is  $P - P^*$ , and the total CS is calculated as  $CS = \int_0^{D^*} (P - P^*) dD = D^{*2}/2b$ , corresponding to the area of the shaded triangle in Fig. 12(a). It is obvious that the CS can also be equivalently formulated as  $CS = \int_{P^*}^{\bar{P}} D dP = \int_{P^*}^{\bar{P}} (a - bP) dP = aP - bP^2/2 \Big|_{P^*}^{\bar{P}} = D^{*2}/2b$ , where  $\bar{P}$  is the intercept of the inverse demand function and represents the highest price of the product that can be sold out.

However, when consumers have green awareness/preference, the market demand becomes price- and greenness dependent, i.e.,  $D = a - bP + \zeta e$ , and the inverse demand curve will shift to the right by a distance of  $\zeta e$ , as Fig. 12(b) shows. At the same selling price  $P^*$ , more consumers will buy the product, and the number of the newly added consumers will be  $D^{**} - D^* = \zeta e$ . At the same time, each consumer’s “willingness to pay” will increase, leading to an increase in the total CS, as shown by the shaded area in Fig. 12(b). We can formulate the CS with green preference as  $CS = \int_{P^*}^{\bar{P}_2} D dP = \int_{P^*}^{\bar{P}_2} (a - bP + \zeta e) dP = aP - (bP^2/2) + \zeta eP \Big|_{P^*}^{\bar{P}_2} = D^{**2}/2b$ , which Huang et al. [3] and Liu et al. [64] have also considered.

Since the expression of  $D^{**}$  contains  $e$ , even though the selling price of the product is the same, the CS will change because of the change in the product greenness.

Returning to our problem, the difference in CS under GOF and TOF can be characterized as  $\Delta CS = CS^{GOF} - CS^{TOF} = (\tilde{e} - e_0^*)(a - p + (\tilde{e} + e_0^*)/2)$ . Based on this, we reformulate the difference in social welfare under GOF and TOF, given in (12) and (13), as

$$\begin{aligned} \widehat{\Delta SW} &= SW^{GOF} - SW^{TOF} = \Delta \pi_R + \Delta \pi_B + \Delta EI + \Delta CS \\ &= (\tilde{e} - e_0^*) \left[ 2a - c - p + \left[ (3 - k)(\tilde{e} + e_0^*) \right] / 2 \right] \end{aligned} \quad (14)$$

Then, the conclusions in Propositions 10 and 11 will change as follows:

**Proposition 12.** Regarding the properties of  $\widehat{\Delta SW}$ , we have

(a) when  $k \leq 3$ ,  $d\widehat{\Delta SW}/dr < 0$  over  $r \in (0, R)$ ;

(b) when  $k > 3$ , there exists a unique  $r_{CS}^{**} \in (0, r^*)$  such that  $d\widehat{\Delta SW}/dr > 0$  over  $r \in (0, r_{CS}^{**})$ , while  $d\widehat{\Delta SW}/dr < 0$  over  $r \in (r_{CS}^{**}, R)$ ;

(c)  $\widehat{\Delta SW}(r \rightarrow R) = 0$  and  $\widehat{\Delta SW}(r = \underline{r}) > 0$ ;

where  $r^*$  and  $\underline{r}$  follow Proposition 8, and  $r_{CS}^{**}$  solves  $\pi_S^{GOF}(r_{CS}^{**}; \tilde{e} = (2a - c - p)/(k - 3)) = \pi_S^{TOF}(e_0^*)$ .

**Proposition 13.** For the case of  $r \in (0, \underline{r})$ , there exists a unique  $\hat{k}_{CS} > 3$  such that

(a) when  $k \leq \hat{k}_{CS}$ ,  $\widehat{\Delta SW} > 0$  always holds over  $r \in (0, \underline{r})$ , then the government will choose to subsidize  $s$  to the bank, and a

portfolio contract  $[r, \bar{e}, s]$  that meets  $\begin{cases} r \in (0, \underline{r}) \\ \bar{e} = \bar{e}(r) \\ s = (\underline{r} - r)L(r) \end{cases}$  can

incentivize all the participants to join GOF and produce higher social welfare than that under TOF.

(b) when  $k > \hat{k}_{CS}$ , there exists a unique  $r'_{CS} \in (0, \underline{r})$  such that for  $r \in [r'_{CS}, \underline{r})$ ,  $\widehat{\Delta SW} \geq 0$  holds, then the government will follow the strategies in part (a) to subsidize; for  $r \in (0, r'_{CS})$ ,  $\widehat{\Delta SW} < 0$ , then the government will not subsidize and the system turns to TOF,

where  $\hat{k}_{CS}$  solves  $2a - c - p + [(3 - k)/2][\tilde{e}_{\max}(k) + e_0^*(k)] = 0$ , in which  $\tilde{e}_{\max}(k)$  is the maximum product greenness in the GOF game and can be solved by  $\pi_S^{GOF}(\tilde{e}_{\max}; r = 0) = \pi_S^{TOF}(e_0^*)$ ; and  $r'_{CS}$  solves  $\pi_S^{GOF}(r'_{CS}, \tilde{e} = [2(2a - c - p)/(k - 3)] - \tilde{e}_0) = \pi_S^{TOF}(\tilde{e}_0)$ .

The conclusions in Propositions 12 and 13 are similar to those in Propositions 10 and 11. After reconsidering the formulation of CS, the difference in social welfare under GOF and TOF, i.e.,  $\widehat{\Delta SW}$ , is still monotonically decreasing or unimodal with respect to the bank’s loan interest rate  $r$ , depending on the value of the supplier’s cost coefficient of green investment  $k$ . For the subsidy decision of the

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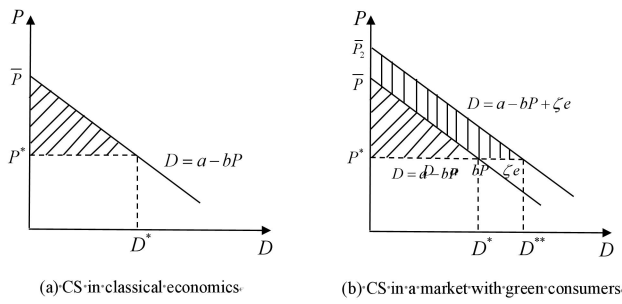
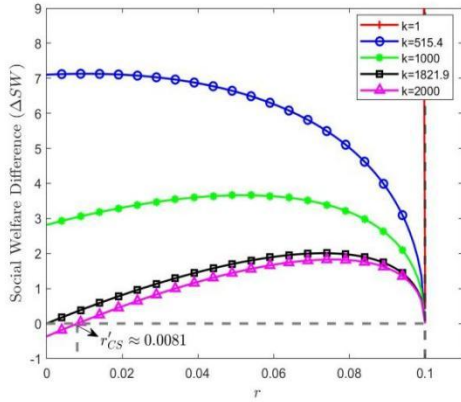


Fig. 12. Diagrams of CS

Fig. 13. Changes in  $\widehat{\Delta SW}$  with  $r$  varying at different  $k$  values

government, when  $k$  is below the threshold  $\hat{k}_{CS}$ , the government will have no hesitation in providing the subsidy; otherwise, it provides the subsidy only when  $r$  is above the threshold  $r'_{CS}$ .

It is clear that  $r'_{CS} < r'$  since  $\tilde{e} (= [2(2a - c - p)/(k - 3)] - e_0^*) > \tilde{e} (= [2(a - c)/(k - 2)] - e_0^*)$ . This shows that the pricing range of the bank's interest rate that leads to  $\widehat{\Delta SW} < 0$  will shrink, implying that the applicable scenarios of government subsidies will expand. This is because the involvement of CS leads to an overall increase in social welfare, making the government more inclined to offer compensation to the bank for participating in GOF, thus broadening the range of the bank's preferential loan interest rate where this subsidy is feasible.

Below, we follow the parameter settings in Section VII. A to perform numerical verification. When further considering CS in formulating the social welfare, the properties of the social welfare difference between GOF and TOF, i.e.,  $\widehat{\Delta SW}$ , are similar to those described in the case without CS. As shown in Fig. 13, there is also a critical value  $\hat{k}_{CS} \approx 1812.9$  such that when the cost coefficient of the supplier's green investment  $k$  is less than  $\hat{k}_{CS}$ ,  $\widehat{\Delta SW}$  will always be positive; otherwise, it will be positive only when the bank's interest rate satisfies  $r > r'_{CS}$ . Comparing Fig. 13 with Fig. 10, we see that  $\hat{k}_{CS} > \hat{k}$  while  $r'_{CS} < r'$  (taking the case of  $k = 2000$  for

observation), which means that after considering the CS, the situation and interval of  $\Delta SW > 0$  will be further expanded, and the government will have greater willingness to incentivize the operations of the GOF system through the subsidy scheme as stated in Proposition 13.

### C. Extension for Considering a Three-level Game

In the above, we considered the decisions of the supply chain members, assuming that the preferential loan interest rate of the bank under GOF is an exogenous variable, and explored the internal and external incentive problems of the GOF system. In this section, we incorporate the bank as a player in a three-level Stackelberg game involving the bank, retailer, and supplier. The sequence of events is as follows: The bank, as the provider of the green financial service, takes the lead in setting a loan interest rate that is most favorable to itself. Then, the retailer, as the supporting party of the green financial service, acts as the subleader and sets a GOF entry threshold for the supplier. Finally, the supplier, acting as the follower, chooses its favorable product greenness based on the decisions made by the bank and the retailer.

On the basis of the analysis in Sections V and VI.A, we identify the unique equilibrium of the above game and the multifaceted performance of the GOF system under such equilibrium, as shown in Proposition 14.

**Proposition 14.** In the three-level GOF game case,

(a) the unique equilibrium of the game is  $(r, \bar{e}, e^*)$ , where  $r = r^*$  and  $\bar{e} = e^* = \tilde{e}(r^*) = (w - c)/k$ ;

(b) it leads to Pareto improvements in the profits of all the three participants, i.e.,  $\pi_B^{GOF} > \pi_B^{TOF}$ ,  $\pi_R^{GOF} > \pi_R^{TOF}$ , and  $\pi_S^{GOF} = \pi_S^{TOF}$ , showing the economic value of GOF compared with TOF;

(c) it brings an improvement in the greenness of the supplier's product, i.e.,  $\tilde{e}(r^*) > e_0^*$ , showing the environmental value of GOF compared with TOF, where  $r^*$  follows that in Proposition 8.

Proposition 14 shows that when the bank acts as a dominant player in the game, the decision equilibrium of the GOF system consisting of the bank, retailer, and supplier will be unique. In such an equilibrium, the greenness of the product will increase compared with the case of TOF, while the interests of all three members will be Pareto-improved, which indicates that the GOF mechanism has dual economic and environmental value. Unlike the results in Section VI, when the bank is a dominant player, it will always be motivated to join GOF, so the external incentives are no longer needed unless the government has a higher green development goal.

### D. Extension for Considering Green Credit Subsidy by Government

This extension section incorporates green credit subsidy provided by government into the green supply chain finance framework. We consider a GOF system comprising a government, a bank, a large retailer, and a supplier with limited capital. The remaining assumptions are similar to those

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in the main model. To encourage sustainable development in the supply chain, the bank provides two financing options. One is TOF (traditional order financing), under which the supplier obtains financing at an interest rate  $R$ . The other is GOF (green order financing), which involves the retailer, on behalf of the bank, to establish a greenness entry threshold  $\bar{e}$ . If the supplier meets or exceeds this greenness threshold, it can access GOF at a lower interest rate  $R - \theta$ , where  $\theta$  is the interest subsidies provided by the government to the bank, which satisfies  $0 < \theta < R$ ; if not, only TOF is available. Under this model setting, the retailer, as the leader, determines the GOF entry threshold  $\bar{e}$ . The supplier, as the follower, then makes decisions based on the retailer's strategy, including whether to opt for GOF and how to optimize both the greenness level of product  $e$ . Specifically, the government is not modeled as a decision-maker, and its interest rate subsidy  $\theta$  is treated as an exogenous variable, consistent with [3], [20], [21]; and the bank solely acts as a financing service provider within the system.

We omit the solution process for the basic decision model. It is clear that the decision structure for both the supplier and the retailer remains consistent with the main model, and the unique equilibrium of the game with the retailer as the Stackelberg leader unchanged. GOF still undeniably provides Pareto improvements in profits compared with TOF, and simultaneously enhances product greenness. Since the bank's profit difference  $\Delta\pi_B > 0$  always holds, our analysis exclusively focuses on the government's incentive strategies for the GOF system, specifically on the changes in social welfare. Adopting the same social welfare definition as in Section VII.B, we simplify the difference in social welfare under GOF and TOF as

$$\begin{aligned} \widehat{\Delta SW} &= SW^{GOF} - SW^{TOF} = \Delta\pi_R + \Delta\pi_B + \Delta EI + \Delta CS \\ &= (\tilde{e} - e_0^*) \left[ 2a - c - p + \left( \frac{3-k}{2} \right) (\tilde{e} + e_0^*) \right] \end{aligned} \quad (15)$$

Based on the analysis of the social welfare difference, we can draw conclusions similar to those in Propositions 12 and 13.

**Proposition 15.** *Regarding the properties of  $\widehat{\Delta SW}$ , we have*

- (a) when  $k \leq 3$ ,  $d\widehat{\Delta SW}/d\theta > 0$  over  $\theta \in (0, R)$ ;
- (b) when  $k > 3$ , there exists a unique  $\theta^* \in (0, R)$  such that  $d\widehat{\Delta SW}/d\theta > 0$  over  $\theta \in (0, \theta^*)$ , while  $d\widehat{\Delta SW}/d\theta < 0$  over  $\theta \in (\theta^*, R)$ ;
- (c)  $\widehat{\Delta SW}(\theta \rightarrow 0) = 0$ ; where  $\theta^*$  solves  $\pi_s^{GOF}(\theta^*; \tilde{e} = (2a - c - p)/(k - 3)) = \pi_s^{TOF}(e_0^*)$ .

**Proposition 16.** *For the case of  $\theta \in (0, R)$ , there exists a unique  $\hat{k}_{CS} > 3$  such that*

- (a) when  $k \leq \hat{k}_{CS}$ ,  $\widehat{\Delta SW} > 0$  always holds over  $\theta \in (0, R)$ , then the government will choose to subsidize  $s = (cd + k\bar{e}^2/2)\theta$

to the bank, and a portfolio contract  $[\bar{e}, s]$  that meets  $\begin{cases} \bar{e} = \bar{e}(r) \\ s = (cd + k\bar{e}^2/2)\theta \end{cases}$  can incentivize all the participants to join GOF and produce higher social welfare than that under TOF.

(b) when  $k > \hat{k}_{CS}$ , there exists a unique  $\theta' \in (0, R)$  such that for  $\theta \in (0, \theta')$ ,  $\widehat{\Delta SW} \geq 0$  holds, then the government will follow the strategies in part (a) to subsidize; for  $\theta \in (\theta', R)$ ,  $\widehat{\Delta SW} < 0$ , then the government will not subsidize and the system turns to TOF,

where  $\hat{k}_{CS}$  solves  $2a - c - p + [(3 - k)/2][\bar{e}_{\max}(k) + e_0^*(k)] = 0$ , in which  $\bar{e}_{\max}(k)$  is the maximum product greenness in the GOF game and can be solved by  $\pi_s^{GOF}(\bar{e}_{\max}; \theta = R) = \pi_s^{TOF}(e_0^*)$ ; and  $\theta'$  solves  $\pi_s^{GOF}(\theta', \tilde{e} = (2(2a - c - p)/(k - 3)) - e_0^*) = \pi_s^{TOF}(e_0^*)$ .

It should be noted that in this extension, there is no spontaneous internal incentive from commercial banks, and the incentive effect entirely relies on external government subsidies. Nevertheless, analysis shows that after incorporating government green credit subsidy into the GOF system, such external incentive strategies can still effectively enhance the economic and environmental performance of supply chain members and conditionally promote the overall social welfare of the system. Although the specific boundaries of the incentive interval change, the conclusions and the key parameters influencing the incentive strategies remain highly consistent with those in the main model.

#### E. Extension for Considering Pricing Decisions

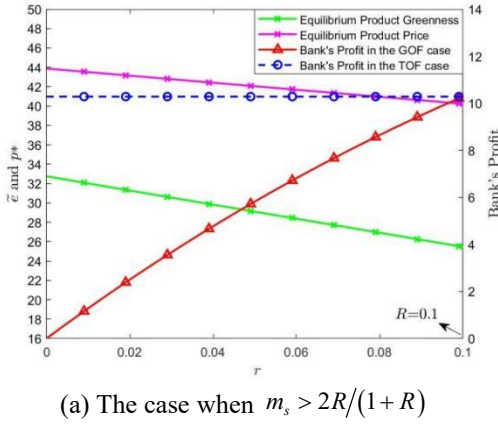
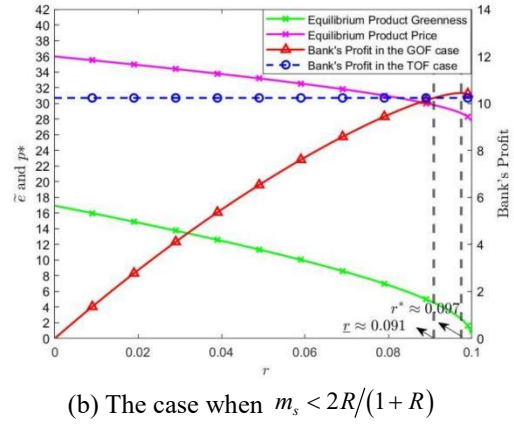
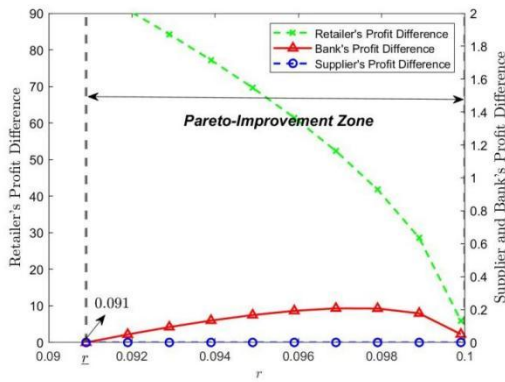
In the main model, pricing decisions are not considered in order to focus on the greenness-related decisions within the supply chain. Since market demand depends on both pricing and greenness, this section further incorporates the retailer's pricing decision into the problem. Specifically, the retailer, as the leader in the game, simultaneously sets the selling price and the GOF entry threshold. The supplier, as the follower, then decides whether to apply GOF and chooses an appropriate level of production greenness.

We first examine the case of TOF, where GOF is not viable, meaning that the GOF entry threshold  $\bar{e}$  does not need to be considered. The supplier's problem remains as described in (1), with the optimal greenness decision being  $e_0^*$ , as shown in Proposition 1. Then, the retailer's problem is described as  $\pi_r^{TOF}(p; e_0^*) = (p - w)(a - p + e_0^*)$ . Solving this, we determine the retailer's optimal pricing decision and conclude the equilibrium of the game as follows:

$$\begin{cases} e_0^* = \frac{w - c(1 + R)}{k(1 + R)} \\ p_0^* = \frac{a + w + e_0^*}{2} \end{cases} \quad (16)$$

Next, we consider the case of GOF, where both TOF and GOF are viable options. Since the greenness is still the unique

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(a) The case when  $m_s > 2R/(1+R)$ (b) The case when  $m_s < 2R/(1+R)$ **Fig. 14.** Numerical analysis verifying Proposition 18**Fig. 15.** GOF system coordination with internal incentives

decision of the supplier, its decision problem remains as described in (3). Consequently, the decision rules for the optimal level of greenness under both GOF and TOF still align with Proposition 2. Therefore, Fig. 2 continues to illustrate the supplier's optimal profit curves under GOF and TOF. As a result, there also exists a unique  $\tilde{e}$ , which is the larger root of  $\pi_S^{GOF}(\tilde{e}, p) = \pi_S^{TOF}(e_0^*, p_0^*)$ . When  $\bar{e} \leq \tilde{e}$ , the supplier applies GOF; otherwise, TOF is chosen. Moreover, the supplier's optimal greenness  $e^*$  continues to depend on  $\bar{e}$ , and its decision rules still follow the structure outlined in Fig. 3 and Proposition 4. Given the supplier's optimal decision rules, the retailer's problem can then be described as

$$\text{Max} \pi_R^{GOF}(\bar{e}, p | e^*) = (p - w)(a - p + e^*). \quad (17)$$

In (17), for any given  $e^*$ , we always have  $p^* = (a + w + e^*)/2$ . This simplifies the problem to maximizing  $\pi_R^{GOF}(\bar{e}, p | e^*) = [(a - w + e^*)/2]^2$ . Therefore,  $\pi_R^{GOF}$  is maximized when  $e^*$  reaches its maximum. From Fig. 3 and Proposition 4, it is evident that when  $\bar{e}$  is set to  $\bar{e} = \tilde{e}$ ,  $e^*$  reaches its maximum, and at this point,  $e^* = \bar{e} = \tilde{e}$  holds. Based on this, we can conclude the optimal GOF entry threshold and pricing decisions for the retailer as  $\bar{e} = \tilde{e}$  and  $p^* = (a + w + \tilde{e})/2$ . Since  $\tilde{e}$  also depends on  $p$ , and given that

$\pi_S^{GOF}(\tilde{e}, p) = \pi_S^{TOF}(e_0^*, p_0^*)$ , we can determine the specific value of  $\tilde{e}$  by solving the system of (18). Finally, we conclude the game equilibrium as described in Proposition 17.

**Proposition 17.** In the case considering the retailer's pricing decision, the GOF game equilibrium between the retailer and the supplier is as follows:

$$\begin{cases} \bar{e} = e^* = \tilde{e} \\ p^* = \frac{a + w + \tilde{e}}{2} \end{cases} \quad (18)$$

where  $\tilde{e}$  is the larger root of

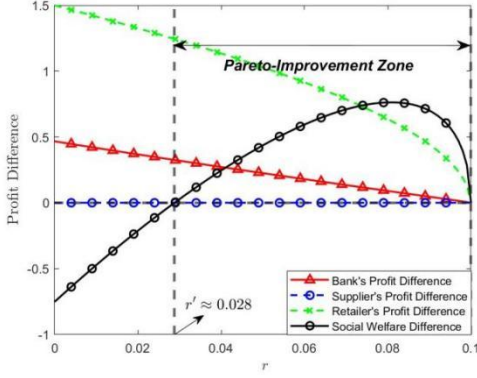
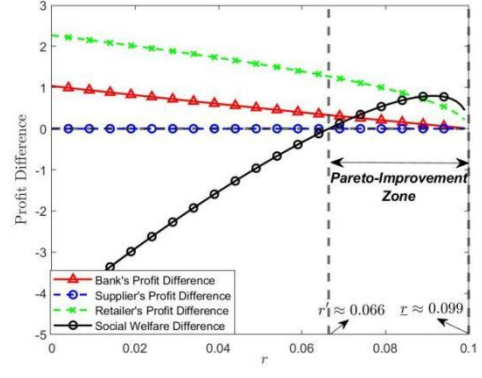
$$-k(1+r)\tilde{e}^2 + [w - c(1+r)]\tilde{e} + c(a-w)(R-r) = 0. \quad (19)$$

Under the equilibrium established in Proposition 17, the supplier's profit under GOF remains the same as that under TOF, while the retailer's profit increases, as  $e^*(=\tilde{e}) > e_0^*$ . Thus, the GOF mechanism results in a Pareto improvement for the supply chain members. Next, we assess whether the bank can benefit from providing GOF. The bank's expected profit under TOF and GOF can be expressed as  $\pi_B^{TOF} = (cd(e_0^*, p_0^*) + ke_0^{*2}/2)R$  and  $\pi_B^{GOF} = (cd(\tilde{e}(r), p^*) + k\tilde{e}(r)^2/2)r$ , respectively. By examining the changes in  $\pi_B^{GOF}$  as  $r$  varies, we can compare  $\pi_B^{GOF}$  with  $\pi_B^{TOF}$  and determine under what conditions  $\pi_B^{GOF}$  outperforms  $\pi_B^{TOF}$ . Defining  $m_s = 1 - (c/w)$  as the unit sales profit margin (referred to as the "profit margin") of the supplier, Proposition 18 summarizes the findings.

**Proposition 18.** In the GOF model considering the retailer's pricing decision:

(a) the equilibrium greenness of the product remains negatively correlated with the preferential loan interest rate, i.e.,  $d\tilde{e}/dr < 0$ ;

(b) if  $m_s < 2R/(1+R)$ , there exists a unique  $r^* \in (0, R)$ , such that when  $r \in (0, r^*)$ ,  $d\pi_B^{GOF}/dr > 0$ ; and when  $r \in (r^*, R)$ ,  $d\pi_B^{GOF}/dr < 0$ . Consequently, there exists a unique  $\underline{r} \in (0, r^*)$ , such that when  $r \in [\underline{r}, R)$ ,  $\pi_B^{GOF} \geq \pi_B^{TOF}$ ; and when  $r \in (0, \underline{r})$ ,  $\pi_B^{GOF} < \pi_B^{TOF}$ ;

(a) The case when  $m_s > 2R/(1+R)$ (b) The case when  $m_s < 2R/(1+R)$ **Fig. 16.** GOF system coordination involving government subsidies ( $k = 2000$ )

(c) if  $m_s \geq 2R/(1+R)$ ,  $d\pi_B^{GOF}/dr > 0$  holds for all  $r \in (0, R)$ , and thus  $\pi_B^{GOF} < \pi_B^{TOF}$ ;

where  $m_s = 1 - (c/w)$  is the supplier's profit margin;  $r^*$  and  $\underline{r}$  solve  $\pi_S^{GOF}(r^*; \tilde{e} = (w-c)/2k) = \pi_S^{TOF}(e_0^*, p_0^*)$  and  $\pi_S^{GOF}(r; \tilde{e} = [(w-c)/k] - e_0^*) = \pi_S^{TOF}(e_0^*, p_0^*)$ , respectively.

Proposition 18(a) indicates that the supplier's product greenness is still negatively correlated with the bank's GOF interest rate. As the interest rate decreases, the supplier's financing amount increases, and the change in the bank's profit, determined by the product of the two, becomes uncertain. As demonstrated in Propositions 18(b) and (c), if the supplier's profit margin is below a certain threshold  $2R/(1+R)$ , the bank will earn more profit from providing GOF than from TOF, as long as it sets a GOF interest rate no less than  $\underline{r}$ . However, if the supplier's profit margin exceeds this threshold, the bank will lose intrinsic motivation to offer GOF, contrasting with Proposition 8. This occurs primarily because the higher profit margin of the supplier weakens its "effort willingness," making its product greenness and financing amount less responsive to the preferential GOF interest rate, which significantly diminishes the bank's expected profit.

Below, we use numerical analysis to verify Proposition 18. Following the parameter settings in Section VII.A (i.e.,  $w = 5$ ,  $c = 2$ ,  $R = k = 0.1$ , and  $a = 50$ ), where  $m_s > 2R/(1+R)$  is satisfied, we observe that as  $r$  decreases from  $R$  to zero, both  $\tilde{e}$  and  $p^*$  increase, while  $\pi_B^{GOF}$  decreases monotonically, as shown in Fig. 14(a). This suggests that  $\pi_B^{GOF} < \pi_B^{TOF}$  for  $r \in (0, R)$ , which verifies Propositions 18(a) and (c). However, when we reset  $c = 4.5$  to meet the new condition  $m_s < 2R/(1+R)$ , the curve of  $\pi_B^{GOF}$  becomes unimodal for  $r \in (0, R)$ , as shown in Fig. 14(b). This implies that  $\pi_B^{GOF} \geq \pi_B^{TOF}$  occurs over  $r \in [\underline{r}, R)$ , thereby verifying Proposition 18(b).

Additionally, in the case where  $\pi_B^{GOF} \geq \pi_B^{TOF}$ , an internal

incentive contract implemented by the bank and the retailer, i.e.,  $[r, \tilde{e}]$ , which meets  $\begin{cases} r \in [\underline{r}, R) \\ \tilde{e} = \tilde{e}(r) \end{cases}$ , can lead to Pareto improvements for all the three GOF members, thus coordinating the GOF system, as shown in Fig. 15.

Furthermore, for the case where  $\pi_B^{GOF} < \pi_B^{TOF}$ , the bank has no intrinsic motivation to provide GOF; thus, an external government subsidy becomes necessary. When  $k$  and  $r$  satisfy certain conditions, similar to those in Propositions 11 and 13, the introduction of GOF results in a positive change in social welfare<sup>14</sup>. Consequently, the government may choose to subsidize the bank, and a portfolio contract  $[r, \tilde{e}, s]$ , similar to those in Propositions 11 and 13, can still incentivize all participants to engage in GOF and generate higher social welfare than in the TOF scenario, as shown in Fig. 16. This also verifies the robustness of the results obtained in Section VI.

## VIII. CONCLUSION

Financing and emission reduction have become two major bottlenecks for SMEs in the supply chain. Increasingly, core enterprises within supply chains are collaborating with banks to offer green order financing (GOF) to their suppliers, helping them secure working capital and reduce emissions. In GOF practices, suppliers must first obtain "green certification" from core enterprises before they can access preferential bank financing to fulfill eco-friendly orders. However, setting a reasonable greenness entry threshold for suppliers' access to GOF poses a significant challenge for core enterprises. A high threshold may deter suppliers from utilizing GOF, whereas a low threshold may undermine the green upgrading of the supply chain. Therefore, this paper explores the establishment of the entry threshold for GOF and proposes incentives to effectively coordinate the GOF system.

In this research, we develop a GOF model involving a bank, a large retailer, and a supplier with limited capital. The retailer,

<sup>14</sup>Note that in this extension, consumer surplus (CS) is considered in formulating the social welfare, similar to Section VII.B.

acting on behalf of the bank, sets the greenness entry threshold for the supplier to access more preferential GOF, leveraging its informational advantages regarding the supplier's environmental performance. We find that the supplier will opt for GOF only when the GOF entry threshold set by the retailer is lower than a critical value; otherwise, it will still use TOF. When the retailer holds a dominant position in the game, a unique equilibrium is achieved between the two parties in the supply chain, under which GOF is implemented and the supply chain obtains Pareto improvements and greenness enhancement. As another participant in the system, the bank can also benefit from providing GOF, as long as it sets a reasonable GOF interest rate, i.e., no lower than a certain threshold. When the GOF interest rate of the bank is below such a threshold, it is necessary to introduce external government incentives. We demonstrate that the government will only refrain from subsidizing the bank if the supplier's cost coefficient of green investment is extremely high while the bank's GOF interest rate is exceedingly low. Otherwise, the government will be willing to provide subsidies (transfer payments) to the bank, resulting in Pareto improvements for all three GOF members and achieving greater social welfare than with TOF. We further extend the analysis by incorporating a new formulation of consumer surplus, a new game sequence, and the retailer's pricing decisions. Our findings reveal that, after considering the impact of greenness enhancement on consumer surplus, the government will be more inclined to subsidize the bank's participation in GOF. This, in turn, expands the range of preferential GOF interest rates where such subsidies remain feasible. When the bank is treated as a player in a three-level game, the decision equilibrium of the GOF system becomes unique, leading to improvements in both economic and environmental performance, thereby eliminating the need for external government incentives. By integrating the retailer's pricing decisions, we find that the bank can achieve incremental profit from providing GOF, as opposed to TOF, only when the supplier's profit margin is relatively low. Otherwise, external government incentives remain essential. The incentive (coordination) schemes proposed in the main study are still applicable, further confirming the robustness of the conclusions. Additionally, we conduct extensive numerical analyses to validate all the key theoretical results presented in this research.

Based on the findings above, we summarize the main managerial implications of this study as follows. First, core retailers play a critical role in promoting Green Order Financing. Through the green certification mechanism led by core enterprises, GOF contributes to Pareto improvement in the overall profit of the supply chain. Therefore, large retailers, such as Walmart, Tesco, and JD.com, should take proactive steps to establish and manage transparent green certification systems, enabling suppliers to access green financing and thereby enhancing the overall green performance of the supply chain. A notable example is PUMA's Green Supply Chain Finance Program, developed in collaboration with the International Finance Corporation (IFC), where the core enterprise leads by offering differentiated financing rates

based on the environmental performance scores of suppliers<sup>15</sup>. Second, as financial service providers, banks must offer preferential GOF interest rates to operationalize the GOF system. This will stimulate green investment and financing among suppliers, thus generating more profits for banks. It should also be noted that preferential GOF interest rate must have a clear lower limit to ensure banks remain motivated for sustained involvement. Thus, banks should balance incentives with profitability when determining interest rate strategies. Moreover, banks can integrate into the supply chain, leverage information advantages to gain a dominant position, and actively engage in GOF decision-making, thereby maximizing profits and managing risks. For example, Huzhou Bank has effectively coordinated financial resources with the green supply chain by actively engaging SMEs and promoting core enterprises' participation in GOF<sup>16</sup>. Third, the government can establish a policy ecosystem aligned with GOF through subsidies. When industry green objectives exceed market-driven incentives, targeted subsidies to banks to overcome interest rate limit can be an effective strategy. This approach could lead to Pareto improvements for all three GOF parties (banks, retailers, and suppliers) and increase overall social welfare. The "government-bank-core enterprise" model, successfully applied in areas like new energy vehicles, provides insights for designing GOF subsidies<sup>17</sup>. It is important to note that the government should monitor the cost-effectiveness of green technologies and emission reduction investments in different industries. Subsidies should be prudently controlled for inefficient emission reduction investments, ensuring that policy resources are allocated to projects with real environmental benefits and transformative potential. Last but not least, GOF involves multiple stakeholders and complex operational mechanisms. The incentive schemes we proposed in Section VI have been shown to be robust in extended studies, enabling practitioners to navigate new decision environments, such as those with new measurements of consumer surplus, new game tier settings, new subsidy categories and new decision variables related to pricing.

The limitation of this paper mainly lies in that we apply the simplest supply chain structure and settings to facilitate the analytical exposition of the study. Future research can tackle more complex decisions and incentives of the GOF system under scenarios such as supply chain competitions [65], uncertain demands [66], [67], non-sequential games [68], imperfect information [69], [70], and so on.

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