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Di Sha

Research on the Production Behavior and Collaborative Regulation of Sustainable Apparel Enterprises under Carbon Emission Constraints and Government Incentives

Thesis defended on 6 November, 2025 before the jury composed of:

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Di Sha

Recherche sur le comportement de production et la régulation collaborative des entreprises d'habillement durable sous les contraintes des émissions de carbone et les incitations gouvernementales

Thèse soutenue le 6 novembre 2025 devant le jury composé de:

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Declaration of Authorship

Di Sha, declare that this thesis titled, “Research on the Production Behavior and Collaborative Regulation of Sustainable Apparel Enterprises under Carbon Emission Constraints and Government Incentives” and the work presented in it are my own. I confirm that:

● This work was done wholly or mainly while in candidature for a research degree at the University of Lille and the Jiangnan University.

● Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

● Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

● Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

Sir Issac Newton

Résumé

Dans un contexte marqué par l’intensification du changement climatique mondial et la généralisation des stratégies de réduction des émissions carbone, les industries traditionnelles à forte intensité énergétique et fortement polluantes subissent une pression de transformation profonde. L’industrie de l’habillement exerce un impact environnemental majeur à travers les émissions de carbone, la consommation d’eau et la pollution chimique. Sa transition constitue ainsi un élément essentiel de l’agenda mondial du développement durable. Toutefois, cette transition est entravée par de multiples défis : incertitude des décisions de production des entreprises, hétérogénéité de la disposition à payer des consommateurs, efficacité limitée des incitations publiques, et absence de mécanismes de régulation sur les plateformes de commerce électronique. Il est donc urgent de mener des recherches systématiques afin de fournir un fondement scientifique et un appui décisionnel efficace pour la formulation des politiques et l’orientation de la transformation du secteur.

La présente étude porte sur l’industrie de l’habillement et examine des facteurs clés tels que les coûts d’émission de carbone, les mécanismes de subvention gouvernementale, la conscience environnementale des consommateurs et la gouvernance des plateformes de commerce électronique. Elle s’articule autour de quatre axes majeurs : les décisions de production des entreprises, la prévision des prix du carbone, les effets des politiques incitatives et la régulation des plateformes. En intégrant des algorithmes d’apprentissage

automatique, des méthodes issues de la théorie des jeux et des techniques de simulation numérique, cette recherche construit un cadre analytique multi-niveaux comprenant un modèle de décision de production unifirme, un modèle de prévision en intervalle du prix du carbone, un modèle de concurrence en duopole, ainsi qu'un modèle de jeu évolutif tripartite. Ce cadre permet de caractériser de manière systématique les interactions stratégiques et les mécanismes de réponse entre entreprises, consommateurs, plateformes et autorités publiques, dans le but de proposer des trajectoires scientifiques et des recommandations politiques pour promouvoir une transition verte et bas-carbone de l'industrie de l'habillement.

Premièrement, sur la base de préférences hétérogènes des consommateurs, ce travail développe un modèle de décision de production pour des entreprises confrontées au choix entre produits traditionnels et produits durables. Le modèle met en évidence les comportements stratégiques optimaux des entreprises sous l'effet de la conscience environnementale, des coûts d'émission de carbone et de la disposition à payer des consommateurs.

Deuxièmement, l'étude propose un cadre de prévision en intervalle des prix du carbone intégrant la sélection de caractéristiques par l'algorithme Extreme Gradient Boosting (XGBoost), un algorithme évolué NSGA-II (Non-dominated Sorting Genetic Algorithm II) et un modèle d'apprentissage profond BiLSTM (Bidirectional Long Short-Term Memory). Cette approche dépasse les limites des modèles traditionnels de prévision ponctuelle face à l'incertitude, et améliore significativement la précision ainsi que la stabilité des prévisions.

Troisièmement, un modèle de concurrence en duopole est construit afin d'analyser comparativement les effets des subventions destinées aux entreprises et de celles orientées vers les consommateurs sur la structure du marché, la tarification des produits, les profits des entreprises et le bien-être social. Les résultats indiquent que les subventions accordées aux entreprises sont plus appropriées dans les premières phases de la transition — lorsque les technologies sont immatures et que les coûts de transformation sont élevés — car elles stimulent efficacement la R&D et l'adoption de technologies vertes.

Enfin, cette étude développe un modèle de jeu évolutif tripartite impliquant producteurs, consommateurs et plateformes de commerce électronique, afin d'explorer les mécanismes de formation et les dilemmes réglementaires liés aux pratiques pseudo-durables sur les plateformes numériques. Les résultats montrent que les décisions des entreprises en matière de production durable sont conjointement influencées par l'intensité de la régulation et les contraintes de coûts ; que les comportements de signalement des consommateurs dépendent des structures d'incitation et des mécanismes de réponse ; et que les stratégies de régulation des plateformes reposent sur un arbitrage dynamique entre gains réputationnels et coûts de supervision.

Abstract

Against the backdrop of intensifying global climate change and the widespread implementation of carbon reduction strategies, traditional high-energy, high-pollution industries are facing profound transformation pressures. The apparel industry significantly impacts the environment through carbon emissions, water consumption, and chemical pollution. Its transformation has thus become a vital component of the global sustainable development agenda. However, the industry's transition is hindered by multiple challenges, including uncertain corporate production decisions, divergent consumer willingness to pay, limited effectiveness of policy incentives, and the absence of regulatory oversight on e-commerce platforms. Therefore, systematic research is urgently needed to provide scientific foundations and effective support for decision-making and policy formulation during the industry's transformation.

This study focuses on the apparel industry, examining key factors such as carbon emission costs, government subsidy mechanisms, consumer environmental awareness, and e-commerce platform governance. It centers on four core themes: enterprise production decisions, carbon price forecasting, policy incentive effects, and platform governance. By integrating machine learning algorithms, game-theoretic approaches, and numerical simulation techniques, this research constructs a multi-level analytical framework comprising a single-firm production decision model, an interval carbon price prediction model, a duopoly competition model, and a tripartite

evolutionary game model. This framework systematically characterizes the strategic interactions and response mechanisms among enterprises, consumers, platforms, and governments, aiming to provide scientific pathways and policy recommendations for a green and low-carbon transition in the apparel industry.

First, based on heterogeneous consumer preferences, this study develops a production decision model for firms facing the choice between traditional and sustainable products. The model reveals the optimal strategic behaviors of enterprises under the influence of environmental awareness, carbon emission costs, and consumer willingness to pay.

Second, this study proposes an interval carbon price forecasting framework that integrates Extreme Gradient Boosting (XGBoost) feature selection, an improved Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization algorithm, and a Bidirectional Long Short-Term Memory (BiLSTM) deep learning model. This approach overcomes the limitations of traditional point forecasting models in dealing with uncertainty and significantly improves forecasting accuracy and stability.

Third, a duopoly competition model is constructed to comparatively analyze the impacts of government subsidies targeting firms versus consumers on market structure, product pricing, corporate profits, and social welfare. The findings indicate that subsidies directed at firms are more suitable for the early stages of transition—when technology is immature and transformation costs are high—as they effectively stimulate R&D and green technology adoption.

Finally, this study develops a tripartite evolutionary game model involving producers, consumers, and e-commerce platforms to explore the formation mechanism and regulatory dilemmas of pseudo-sustainable practices on digital platforms. Results show that firms' decisions to engage in sustainable production are jointly influenced by regulatory intensity and cost constraints; consumer reporting behavior is affected by incentive structures and response mechanisms; and platform regulatory strategies involve a dynamic trade-off between reputational gains and regulatory costs.

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Dissemination

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List of abbreviations

AIW: Average interval width

BiLSTM: Bidirectional long short-term memory

CWC: Coverage width criterion

GRU: Gated recurrent unit

IBEA: Indicator-based evolutionary algorithm

KDE: Kernel density estimation

LSTM: Long short-term memory

MI: Mutual information

MoOPC: Multi-objective optimization problem with constraints

MOEA: Multi-objective evolutionary algorithm

MOEA/D: Multi-objective evolutionary algorithm/decomposition

MSA: Modified scaling approach

NSGA-II: Non-dominated sorting genetic algorithm-II

PICP: Prediction interval coverage probability

PI: Prediction interval

QR: Quantile regression

RFE: Recursive feature elimination

RR: Ridge regression

SA: Scaling approach

TCN: Temporal convolutional network

XGBoost: Extreme gradient boosting

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1. Introduction

1.1. Research context and problem statement

Global warming continues to intensify, with the average global surface temperature from 2011 to 2020 rising approximately 1.1°C compared to the period from 1850 to 1900, causing widespread and profound changes in the atmosphere, oceans, cryosphere, and biosphere (Akram et al., 2022; Fernandez et al., 2022; IPCC, 2021). Climate change driven by human activities has significantly increased the frequency and intensity of extreme weather and climate events, leading to adverse impacts on ecosystems and severe economic losses worldwide (IPCC, 2023; Ermini et al., 2024). Currently, nearly all industrial sectors contribute to environmental pollution to varying degrees.

Among these, the apparel industry stands out for its particularly significant and worsening environmental impacts (Haseeb et al., 2020; Stanton et al., 2023; Raju and Kumar, 2025). The sector accounts for approximately 5–10% of global greenhouse gas emissions (Zhang et al., 2022), with its lifecycle carbon footprint ranking second only to the oil and gas industry—exceedingly even the combined emissions of international aviation and shipping (Boström and Micheletti, 2016; European Parliament., 2022; Niinimäki et al., 2020; Leal et al., 2022). Furthermore, the industry utilizes around 15,000 types of dyes and chemicals and generates approximately 92 million tons of textile waste annually, contributing to nearly 20% of global water pollution (Imran et al., 2023; Fidan et al., 2024).

Environmental studies is an interdisciplinary field that investigates the complex interactions between human activities and ecological systems. Its primary goal is to mitigate the adverse impacts of industrialization, globalization, and consumerism on the environment, while promoting sustainable development pathways. Conducting such studies helps address global challenges such as climate change, environmental degradation, and resource depletion, which threaten both ecological balance and socio-economic stability. To this end, this study conducts four interrelated investigations:

It is essential to verify whether carbon emission costs significantly influence the production strategies of apparel enterprises. Furthermore, accurate carbon price forecasting can serve as a crucial market signal, guiding firms in adjusting their production strategies. However, due to the high transformation costs, relying solely on market mechanisms is insufficient to drive enterprises toward sustainable transitions. Therefore, government subsidies play a vital role in overcoming financial and technological barriers. At the same time, the introduction of subsidies and sustainability labels may be exploited by some firms as tools of opportunism, resulting in greenwashing that undermines policy effectiveness and erodes consumer trust. Consequently, integrating carbon price forecasting, production strategies, government subsidies, and greenwashing into a unified analytical framework facilitates a comprehensive understanding of the corporate strategies, policy interventions, and regulatory challenges, thereby systematically outlining the apparel industry's pathway toward sustainable transformation.

1.1.1. Carbon price forecasting

Against this backdrop, how to effectively regulate carbon emissions through market mechanisms and guide high-emission industries such as the apparel sector toward green transformation has become a focal point of interest for both academia and industry (Haseeb et al., 2020; Nong et al., 2021; Tsai et al., 2022; Xu et al., 2023). Globally, carbon trading markets have emerged as a vital tool for controlling greenhouse gas emissions. Currently, multiple carbon trading systems have been established in regions such as the European Union and China. These systems operate under a "cap-and-trade" mechanism, providing incentives for emission reduction among industrial enterprises. On one hand, rising carbon prices significantly increase the cost of conventional energy sources, compelling firms to accelerate their transition toward sustainable energy. On the other hand, the revenues generated from quota trading can be reinvested in the development of low-carbon technologies, thereby offering robust economic support for emission reduction efforts (Ji et al., 2022; Zhu et al., 2023; Chen and Zhao, 2024).

With the increasing importance of carbon markets, carbon price prediction has become a crucial field of academic research (Habib and Nahia, 2024; Mao and Yu, 2024). Accurate forecasting of carbon price fluctuations not only assists enterprises in carbon asset management and risk mitigation, but also provides quantitative evidence for governments in formulating and adjusting environmental policies (Li et al., 2024).

At present, research on carbon price forecasting has mainly emphasized point forecasts, which generate deterministic predictions and fail to account for uncertainty. In contrast, interval forecasts address these limitations by quantifying uncertainty through lower and upper bounds for predicted values. However, most interval forecasting models depend on parametric methods, which assume that datasets follow a specific known distribution. In real-world scenarios, data distributions can be arbitrary and may not conform to predefined statistical assumptions.

1.1.2. Production strategies for apparel enterprises

With the continuous improvement of carbon trading systems, corporate carbon emission behavior is increasingly subject to market-based constraints (Shrivastava et al., 2021; Abbate et al., 2024). Carbon prices not only reflect the environmental external costs of carbon emissions but also substantially reshape firms' operational logic and resource allocation strategies. Against this backdrop, high-carbon industries, especially apparel manufacturing enterprises with high carbon intensity—are urgently required to adjust their production strategies in response to carbon price signals (Bianco et al., 2021; Masud et al., 2021). Doing so can help reduce compliance costs, enhance competitiveness, and achieve sustainable development goals (Dulal et al., 2025; Deogaonkar-Baride et al., 2025). In addition, growing consumer environmental awareness, stricter carbon regulations, and rising sustainability requirements from international brands have driven an increasing number of apparel companies to proactively explore sustainable production pathways (Felice et al., 2025).

On the demand side, the rise of sustainable fashion has become increasingly prominent, with a growing number of consumers inclined to purchase sustainable clothing (Schiaroli et al., 2024). This shift in consumer preferences not only reflects heightened public environmental awareness but also presents new market opportunities and challenges for enterprises (Feng and Ngai, 2020; Ali et al., 2024). On one hand, sustainable clothing often involves higher production costs and consequently higher retail prices, which may limit its market penetration. On the other hand, firms that continue to rely on traditional production models may face rising carbon costs, greater risks of regulatory non-compliance, and reputational damage (Lu et al., 2023; Huang et al., 2024; Wen et al., 2025).

However, existing studies primarily focus on the influence of factors such as environmental awareness, price sensitivity, and brand trust on consumers' purchasing behavior toward sustainable apparel, while relatively little attention has been paid to how consumer heterogeneity affects the production behavior of apparel firms. In addition, the current literature on enterprise production decision-making models generally overlooks the increasingly significant role of carbon emission costs, failing to thoroughly reveal the mechanisms through which such costs influence the adjustment of production strategies in apparel enterprises.

1.1.3. Government subsidies

In the process of proactive transformation by apparel enterprises, relying solely on market mechanisms and firms' self-regulation often proves insufficient to overcome the substantial challenges encountered during the early stages of transformation, such as high upfront investment costs, technological uncertainty, and delayed market responses. Since sustainable transformation typically entails a systemic restructuring of production processes, supply chain systems, and end products, the initial capital investment and operational risks pose considerable obstacles for most enterprises. As a result, governments play a crucial guiding and supportive role in promoting sustainable development within the apparel industry.

Government subsidies, as a typical policy instrument, can provide external incentives to both firms and consumers, thereby compensating for market failures in resource allocation and alleviating financial constraints and technological barriers faced by enterprises during the transformation process. Studies have shown that government subsidies significantly enhance firms' capabilities for sustainable technological innovation. Specifically, subsidies not only effectively motivate apparel companies to increase their R&D investment in sustainable technologies and improve the output ratio and market competitiveness of sustainable clothing, but also help reduce the cost or increase the accessibility of green products, thereby boosting consumer awareness and willingness to purchase sustainable apparel (Chen et al., 2023; Zhang et al., 2024).

However, existing studies have mostly adopted qualitative perspectives to examine the factors influencing consumers' sustainable awareness and the effectiveness of government subsidies, lacking systematic analysis based on quantitative methods regarding the mechanisms through which subsidies exert their impact. Moreover, much of the current research takes the sustainable apparel supply chain as the primary analytical framework, without adequately considering the market competition between traditional apparel firms and sustainable apparel firms driven by policy incentives. Consequently, there are limitations in revealing how government subsidies influence firm behavior through market mechanisms.

1.1.4. Greenwashing

However, despite the positive role of government subsidies in promoting green transformation within the industry, certain policy loopholes and regulatory blind spots have emerged in the course of their implementation. As subsidy resources increasingly favor sustainable products, some enterprises have begun to exploit sustainability certifications as tools for market competition, even resorting to false declarations and other deceptive practices to gain policy benefits. This behavior has gradually evolved into the phenomenon known as greenwashing.

In particular, with the rapid development of e-commerce, sustainability labeling systems introduced by online platforms have become important instruments for guiding green consumption (Behre and Cauberghe, 2025). However, due to the lack of effective regulatory oversight, some companies have taken advantage of these systems to obtain “sustainable” certifications through misleading marketing or superficial compliance, while their actual production processes fall short of environmental standards (Li and Zhong, 2025). The widespread occurrence of greenwashing has led to a range of negative consequences. From the consumer perspective, false sustainable products erode public trust in sustainability certifications and undermine the foundations for promoting green consumption. From the industry perspective, greenwashing disrupts fair market competition, placing genuine innovators and firms committed to green technology at a disadvantage, thereby contributing to a "race to the bottom" scenario in which dishonest behavior drives out responsible actors (Liu et al., 2025).

Although existing research has recognized the detrimental effects of greenwashing, most studies remain at the level of static description and have not adequately revealed the dynamic game processes among key stakeholders under the influence of policy incentives and market feedback. In particular, there is a lack of quantitative analysis of strategic interactions and evolutionary trajectories among firms, platforms, and consumers. Furthermore, although some scholars have noted that the rise of the platform economy presents new challenges for green governance, there has been little systematic exploration of the dual-role tension faced by platforms in addressing greenwashing. On the one hand, as standard-setters and dominant allocators of market resources, platforms may loosen certification thresholds to maximize transaction volumes under commercial pressures. On the other hand, they are also expected to act as ecological regulators, upholding platform credibility and consumer trust.

1.2. Research questions and objectives

As discussed above, the apparel industry has become one of the primary drivers of global greenhouse gas emissions and environmental degradation. With the refinement of carbon market mechanisms and the rise in consumer environmental awareness, apparel firms are under increasing pressure to transition toward sustainable production models. However, this transition is hindered by multiple challenges: the uncertainty of carbon pricing mechanisms, the complexity of government subsidy policies, and the widespread presence of greenwashing behaviors on e-commerce platforms. To address these issues, this study centers on four interrelated research questions, each selected to capture a critical dimension of the sustainable transformation pathways:

RQ1: How do carbon costs and consumer heterogeneity influence apparel firms' sustainable production strategies?

This problem is chosen because understanding the combined impact of carbon emission costs and heterogeneous consumer preferences is fundamental to explaining firms' production behaviors under evolving market and policy constraints.

RQ2: Can deep learning models effectively forecast carbon price intervals to inform production decisions?

This problem is selected because reliable interval forecasting of carbon prices not only advances methodological innovation but also provides firms with robust decision-making signals in the face of market uncertainty.

RQ3: How do government subsidies (producer- vs. consumer-oriented) impact strategic decisions, competition, and social welfare in duopolistic apparel markets?

This problem is included because government subsidies remain one of the most widely used instruments for correcting market failures, yet their differential impacts on firm competition and welfare outcomes in the apparel sector are not fully understood.

RQ4: How can collaborative regulation mitigate greenwashing behaviors in online apparel markets?

This problem is selected because the proliferation of greenwashing undermines both consumer trust and policy effectiveness; analyzing collaborative regulatory mechanisms is therefore essential for ensuring fair competition and credible sustainability transitions.

Based on the above research questions, the study sets forth the following research objectives:

RO1: To incorporate carbon emission costs and consumer heterogeneity into apparel firms' production decision models, and analyze their impacts on firms' production strategies.

RO2: To develop a deep learning-based carbon price interval forecasting model that quantifies the uncertainty of carbon price fluctuations.

RO3: To evaluate the strategic and welfare implications of various government subsidy designs in duopolistic settings, contributing to optimal policy formulation.

RO4: To construct a collaborative regulatory mechanism that moderates opportunistic behaviors on e-commerce platforms.

1.3. Research outline and contributions

1.3.1. Research outline

Chapter 3: Single-firm decision-making.

This chapter aims to examine how a single apparel firm can optimize its production strategy in the context of increasingly mature carbon market mechanisms and heterogeneous consumer preferences. By developing a dual-product decision-making model that includes both conventional and sustainable apparel, and incorporating carbon emission costs and consumer environmental awareness as key variables, the chapter further employs numerical simulations to identify the boundary conditions and path dependencies of strategic adjustments under varying carbon prices and levels of environmental awareness. This analysis lays theoretical groundwork for subsequent chapters on carbon price uncertainty quantification and duopoly market competition.

Chapter 4: Carbon price interval forecasting via hybrid deep learning.

This chapter shifts focus to the problem of modeling carbon price uncertainty and proposes a hybrid deep learning-based interval forecasting method to provide apparel firms with dynamic and robust carbon cost expectations for decision-making. Existing carbon price forecasts primarily rely on point prediction methods, which fail to capture the significant volatility and sensitivity of carbon prices, and often depend on strong assumptions about error distributions. To overcome these limitations, this study designs a forecasting framework that integrates feature selection mechanisms, deep temporal models, and an asymmetric scaling approach optimized through multi-objective optimization techniques, thereby improving both predictive accuracy and robustness.

Chapter 5: Duopoly under government incentives.

This chapter constructs a duopoly market competition model to investigate how government subsidy policies influence the sustainable transition of the apparel industry. It systematically analyzes the impacts of different subsidy targets (producers vs. consumers), levels of consumer environmental preference, and subsidy intensity on the production decisions, pricing mechanisms, market structure, and social welfare outcomes of conventional and sustainable apparel firms.

Chapter 6: Regulation of greenwashing on e-commerce platforms.

This chapter focuses on the increasingly prominent issue of greenwashing on apparel e-commerce platforms. An evolutionary game-theoretic approach is employed to construct a tripartite game model involving producers, consumers, and platforms. The analysis investigates how platforms can effectively curb greenwashing behavior through collaborative governance mechanisms under the widespread application of sustainability labeling systems.

In summary, Chapter 3 establishes how carbon costs and consumer heterogeneity shape firms' production decisions; Chapter 4 offers a methodological contribution by developing robust carbon price interval forecasting; Chapter 5 introduces the government subsidy mechanism and explores its impact on production behavior; and Chapter 6 investigates pathways for governing greenwashing behaviors on e-commerce platforms. The specific roadmap is illustrated in Fig. 1.1.

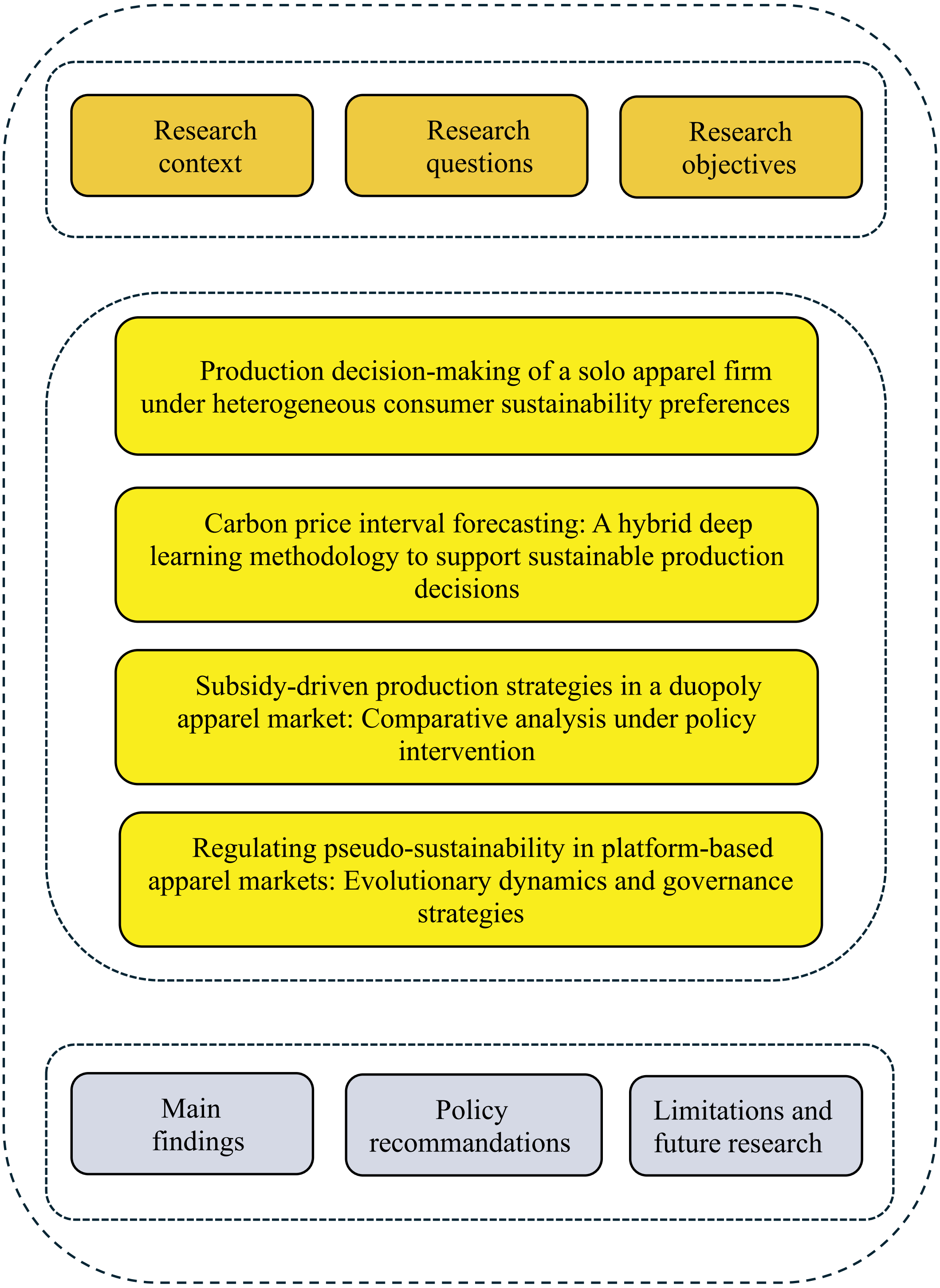


Fig. 1.1. Roadmap

1.3.2. Research contributions

In this study, we systematically address the aforementioned four key issues, providing both theoretical foundations and practical guidance for apparel enterprises transitioning toward sustainable production. The primary contributions are manifested in the following aspects:

(1) **Strategy Optimization Analysis at the Individual Firm Level**: This study constructs a dual-product-line decision model encompassing both traditional and sustainable products, revealing the interaction between carbon emission costs and consumer heterogeneity in corporate production decisions, as well as their path-dependent characteristics. The findings offer theoretical support for understanding firm behavior under carbon market mechanisms.

(2) **Innovative Interval Forecasting Method for Carbon Price Uncertainty**: We propose a hybrid deep learning prediction framework integrating feature selection, deep temporal modeling, and asymmetric scaling techniques, overcoming the limitations of traditional point forecasting methods in modeling carbon price volatility. This provides firms with a more robust tool for anticipating carbon costs.

(3) **Systematic Evaluation of Government Subsidy Policy Effects in a Duopoly Market**: By developing a duopoly competition model incorporating different subsidy mechanisms and consumer preferences, this study elucidates the boundary conditions and mechanisms through which government intervention promotes sustainable apparel development, offering quantitative references for policymaking.

(4) **Exploration of "Greenwashing" Regulation Mechanisms from a Platform Governance Perspective**: Employing evolutionary

game theory, we model the tripartite interaction among firms, consumers, and platforms under sustainable labeling mechanisms. The study examines the effectiveness of platform-based collaborative governance strategies in curbing greenwashing behaviors, thereby fostering a healthier green consumption environment.

This research advances both theoretical and practical insights into sustainable transformation in the apparel industry, bridging critical gaps in firm-level decision-making, carbon market forecasting, policy evaluation, and governance mechanisms.

2. Related work

2.1. Sustainable consumption

2.1.1. Sustainability premium in apparel

From a business perspective, consumers' willingness to purchase sustainable apparel is a key driving force for enterprises to maintain sustainable production practices (Schiaroli et al., 2024; Dethier et al., 2025; Helinski et al., 2025). Although consumers generally acknowledge the environmental benefits of sustainable clothing, actual purchase behavior remains limited (Lim et al., 2023). This inconsistency between consumers' environmental awareness and their purchasing behavior is referred to as the sustainable purchase gap, highlighting the disconnect between pro-environmental attitudes and actual buying decisions (ElHaffar et al., 2020; Fatma and Sukru, 2024). For instance, Zalando SE, Europe's largest fashion retailer, reported that while 58% of consumers recognize the importance of sustainable fashion, only 23% take corresponding actions, and 81% rarely consider sustainable fashion in their purchase decisions (Heiny et al., 2021).

A core reason for this gap lies in the sustainability premium—that is, the generally higher retail prices of environmentally friendly apparel compared to conventional products (Harris et al., 2016; Niinimäki et al., 2020; Islam et al., 2022). This premium arises primarily from three cost components: (1) Material Costs: Sustainable fabrics, such as organic cotton and recycled fibers, are typically more expensive. (2) Compliance Costs: Meeting environmental regulations—such as low carbon emissions and non-polluting production processes—increases operational expenditures. (3) Supply Chain Costs: Implementing sustainable practices throughout the supply chain, including fair trade protocols and green energy usage, requires additional investments (Goworek et al., 2012). These factors collectively raise production costs for firms, which are eventually passed on to consumers in the form of higher retail prices. As a result, although consumers may express favorable attitudes toward sustainable apparel, price sensitivity often drives them to opt for more economically advantageous conventional clothing (Magnier et al., 2019).

It can be observed that most studies remain at the level of describing consumers' price sensitivity and the resulting "sustainable purchasing gap," while lacking systematic modeling of price formation mechanisms, heterogeneity in consumers' willingness to pay, and the dynamic evolution of price premiums.

2.1.2. Sustainable apparel consumption

Resource scarcity and environmental degradation have become prominent challenges affecting global socio-economic development (Dissanayake and Weerasinghe, 2022; Valencia et al., 2025). Promoting sustainable development is a critical strategy for achieving green transformation and low-carbon growth. As one of the key participants in economic activities, consumers' purchasing behavior toward sustainable apparel directly influences firms' decisions regarding sustainable technology innovation and thereby shapes the trajectory of industrial and economic development. In recent years, as the principles of sustainable development have gained wider traction and consumer environmental awareness has grown, a majority of consumers are more inclined to choose sustainable apparel over conventional alternatives, all else being equal (Bhattacharya and Sen, 2004). Studies have shown that 71% of consumers report considering the environmental impact of products when making purchase decisions (Elving et al, 2015).

However, sustainable apparel—often driven by innovative and eco-friendly technologies—tends to be priced higher than conventional garments. Influenced by traditional consumption patterns, such as self-interest, unconscious social imitation, and short-termism, even environmentally conscious consumers may be reluctant to pay a price premium for sustainable products, and may hesitate to translate their environmental attitudes into actual purchasing behavior (Griskevicius et al, 2012; Ramayah et al, 201). Furthermore, skepticism about the quality, functionality, applicability, and companies' actual environmental commitment to sustainable products may also hinder the development of the sustainable apparel market. As a relatively new product category, the widespread adoption of sustainable apparel undeniably requires a behavioral shift among consumers toward more environmentally responsible purchasing practices. Therefore, studying consumers' sustainable consumption behavior is a necessary precondition for achieving sustainable development goals, particularly in the context of promoting a sustainable and green economy.

The above studies often overlook the interactive effects between consumers and firms, namely, how consumer behavior in turn shapes firms' production strategies and the overall market structure.

2.1.3. Environmental awareness

Environmental awareness is widely recognized as a key factor influencing consumers' sustainable behavior and their willingness to purchase sustainable apparel. It is typically defined as an individual's cognitive understanding, level of concern, and behavioral tendency toward environmental issues (Despotović et al., 2021; Busalim et al., 2022; Dangelico et al., 2022; Mandarić et al., 2022). Scholars generally agree that enhancing environmental awareness is a fundamental driver for achieving sustainable development goals (Zsóka et al., 2008; Apaolaza et al., 2023; Yang et al., 2024). Its influence operates on two levels: at the micro level, it promotes individual environmentally friendly practices; at the macro level, it facilitates the cultural transformation of society toward a sustainability-oriented paradigm (Turunen and Halme, 2021; Laukkanen and Tura, 2022; Liang et al., 2024).

Currently, the development of environmental awareness shows significant regional disparities. Compared with consumers in mature markets, those in emerging markets tend to exhibit relatively lower levels of environmental consciousness (Wang et al., 2021; Donato et al., 2022; Sigurdsson et al., 2022; Najafabadiha et al., 2025). Under conditions of information asymmetry, these consumers often display a price-sensitive orientation, which diminishes the weight of environmental benefits in their purchase decisions (Cook et al., 2023). However, with the increasing dissemination of sustainability-related information, enhanced environmental awareness tends to exert a dual moderating effect: sensitivity to information processing and decision-making trade-off capability. These refer, respectively, to the consumer's heightened attention to environmental attributes and the improved ability to balance price and environmental factors during purchase decisions (Meise et al., 2014; Shehawy, 2023). This cognitive transformation suggests that when environmental awareness reaches a certain threshold, it can effectively override traditional price-dominant decision-making models, providing a new explanatory framework for understanding sustainable consumption behaviors (Alhamad et al., 2023; Berden and Hung, 2025; Donato and Adıgüzel, 2025; Yao et al., 2025).

The above studies often neglect the moderating role of environmental awareness in multi-party interactions, such as how it influences consumer reporting of greenwashing, promotes firms' green innovation, or enhances policy effectiveness.

2.2. The influence of consumers on sustainable technological innovation

As consumer attention toward sustainable apparel increases and firms become more proactive in developing sustainable products, there is growing interest in the environmental improvements that such developments may bring. As key participants in the market, consumers are a primary determinant of enterprise profitability. Therefore, sustainable consumption behaviors directly influence firms' willingness to invest in and adopt sustainable technologies, thereby contributing to environmental improvements (Yalabik, and Fairchild, 2011).

Several studies have examined the impact of sustainable consumer behavior on corporate innovation and environmental outcomes from the consumer perspective. For instance, Rodríguez-Ibeas (2007) constructed a duopoly model incorporating both conventional and sustainability-oriented consumers to study the influence of environmental awareness. In the model, sustainable consumers value both physical and environmental attributes of products, whereas conventional consumers focus solely on physical attributes. The study concluded that when the marginal cost of producing sustainable products is relatively low, an increase in consumer environmental awareness contributes positively to environmental outcomes. Brécard (2013) investigated how consumer environmental consciousness and firm competition affect environmental quality and product pricing. The study assumed that the growing number of green-conscious conventional consumers enhances the satisfaction level of each sustainable consumer. Results showed that when the network effects of sustainable products exceed those of conventional products, these externalities increase the consumption of sustainable products but may reduce their environmental quality. Conversely, when conventional products exhibit stronger network effects, the externalities improve environmental quality but lead to increased consumption of non-green products. In both cases, the overall pollution level remains unaffected by network effects. To correct for such externalities, three optimal fiscal tools were proposed: ad valorem taxes, emission taxes, and subsidies—or taxes on sustainable purchases as a second-best alternative.

From the firm perspective, while the adoption of sustainable technologies may enhance a company's market appeal, firms remain cautious. This is largely due to the substantial upfront capital investments and increased variable costs associated with most sustainable technologies. As a result, firms tend to adopt a wait-and-see attitude when considering investments in sustainable R&D (Krass et al., 2013). Additionally, since sustainable products cause less environmental harm but are typically more expensive, their market penetration remains relatively limited. Therefore, a firm's decision to adopt sustainable technologies is influenced by multiple factors. Chen et al. (2013) analyzed the interaction between consumer preferences, producer strategies, and government regulations, and explored from a monopolist's perspective whether it is optimal to develop sustainable products. Yenipazarli, and Vakharia (2015) argued that substituting conventional products with sustainable alternatives can enhance competitiveness. Zhang et al. (2013) examined how consumer environmental awareness and energy-efficiency standards impact optimal investment in sustainable technologies.

Most studies merely distinguish between "sustainable consumers" and "conventional consumers," while overlooking heterogeneity in consumers' willingness to pay, the intensity of environmental awareness, and price sensitivity. The lack of in-depth exploration of stratified consumer behaviors makes it difficult to uncover the differentiated driving effects of various consumer groups on firms' technological investments.

2.3. The impact of government subsidies on sustainable technological innovation

Government subsidies constitute a significant area of research within the domain of sustainable economics. Xepapadeas et al. (1991) found that when consumers involuntarily internalize the external environmental impacts, public policy interventions such as through subsidies, which is essential for achieving environmental protection goals. Mahenc (2008) argued that because sustainable products offer higher environmental benefits but also require greater technological investment, their prices are often higher than those of conventional products. This price gap may incentivize opportunistic manufacturers to misrepresent conventional products as sustainable ones. Government intervention through public policy is thus necessary to curb such behavior and maintain market integrity. Chen and Sheu (2009) pointed that governments can raise environmental standards incrementally through policy adjustments, thereby motivating manufacturers to enhance the recyclability of their products. Over time, such policies also foster a shared sense of responsibility toward sustainability among both producers and consumers. In assessing the effect of subsidies for green products, Chang et al. (2013) evaluated the maximum emissions reduction outcomes of Taiwan's subsidy policy for solar water heaters, highlighting the environmental efficacy of targeted subsidy programs.

Yang (2010) synthesized effective government subsidy strategies across countries and applied game theory to analyze the strategic interactions among governments, firms, and consumers. The study concluded that subsidies should primarily target consumers. Yang and You (2021) argued that although subsidizing either producers or consumers may lead to equivalent market shares and social welfare outcomes, consumer subsidies are more cost-effective in terms of implementation. Zhu and Dou (2011) constructed a game-theoretic model based on consumers' willingness to pay and examined a dual-subsidy scenario involving both producers and consumers. They analyzed the influence of subsidies on firms producing low carbon versus conventional products and found that government subsidies significantly enhance the market share of sustainable products.

Collectively, these studies confirm that government subsidies are one of the most effective instruments for encouraging firms to engage in sustainable technological innovation. However, some research gaps remain. While much of the literature focuses on how subsidy policies influence firm decision-making, less attention has been given to the effectiveness of such subsidies to impact the consumer willingness to pay. In reality, government subsidy policy, consumer premium payment behavior, and enterprise decision-making are interdependent. Ignoring the influence of either consumers or producers may prevent subsidy policies from achieving their intended outcomes—or render them ineffective altogether. This study addresses this gap by incorporating all three elements into a unified system, enabling a more comprehensive assessment of their interactions and collective impact on sustainable innovation.

2.4. The influencing factors of carbon prices

Current research on carbon price forecasting can be broadly divided into two approaches: one that relies on historical data and another that incorporates influencing factors (Deng et al., 2024). The former considers carbon prices as time series data (Jianwei et al., 2021). However, carbon prices are not only influenced by their historical values but also by external factors such as interest rates, exchange rates (Zhang et al., 2021), commodity prices (Han et al., 2019), stock indices, energy indices (Huang and He, 2020) and market sentiment (Li et al., 2024). However, incorporating too many external influencing factors does not necessarily lead to better predictive performance. Redundant features may introduce noise, mask the true influence of critical variables, and ultimately compromise the accuracy of predictions (Sun et al., 2024).

Eliminating irrelevant features from high-dimensional data is essential. Feature selection, a predominant technique for this purpose, is typically classified into three primary approaches：filter, wrapper and embedded methods (Hancer et al., 2018). The filter-based method is recognized for its rapid computational speed, yet it may overlook interactions between features (Jović et al., 2015). The wrapper-based method provides an accurate assessment of feature contributions to the model but incurs significant training time and is prone to overfitting. The embedded-based method, which integrates feature selection within the model training process, accounts for feature interactions and generally exhibits superior performance in identifying relevant features.

Existing studies predominantly rely on a single feature selection method, without leveraging the complementary advantages of multiple approaches. Moreover, there is a lack of systematic comparison and empirical validation of different feature selection methods in the context of carbon price forecasting.

2.5. **Forecasting models of carbon prices**

As mentioned in the introduction, mainstream prediction models can be categorized into three primary types: statistical models, deep learning and hybrid models (Li et al., 2021; Zhang et al., 2023; Lin et al., 2024). Statistical models are suitable for capturing linear patterns, rely solely on historical carbon price data for forecasting, such as autoregressive (AR), generalized autoregressive conditional heteroskedasticity (GARCH), and autoregressive moving average (ARMA) (Zhao et al., 2021; Wang et al., 2023; Zhang et al., 2024).

Deep learning models are suitable for handling non-linear data (Wang et al., 2022). Notable examples include recurrent neural network (RNN), known for capturing short-term dependencies in time series (Nadirgil, 2023), long short-term memory (LSTM) valued for its ability to effectively capture long-term dependencies in time series (Zhou et al., 2022), bidirectional long short-term memory (BiLSTM) preferred for simultaneously considering historical and future information (Zhang et al., 2023), temporal convolutional network (TCN) valued for feature extraction capabilities (Yang et al., 2024), Transformer selected for directly modeling global relationships in time series (Sun et al., 2024) and gate recurrent unit (GRU) appreciated for computational efficiency and generalization (Tian et al., 2024). However, due to their inherent limitations, the above single prediction models often fail to achieve consistently superior forecasting performance across all datasets (Han et al., 2019; Jianwei et al., 2021; Li et al., 2021; Min et al., 2022; He et al., 2024).

To address the limitations of individual models, hybrid approaches have been developed that combine the strengths of various techniques and algorithms, offering a more robust predictive framework (Zhao et al., 2018; Afshari et al., 2022). These methods often integrate data preprocessing strategies, deep learning architectures, and optimization algorithms, and are considered among the most effective prediction techniques (Lin and Xu, 2021; Liu et al., 2023; Li and Ren, 2023; Zhao et al., 2024; Zhu et al., 2025). For instance, Cao et al (2024) proposed a hybrid model that integrates BiLSTM with an attention mechanism and the Sparrow Search Algorithm for power load forecasting, achieving outstanding predictive performance.

It can be observed that statistical models are inadequate in capturing nonlinear features, while deep learning models, though capable of handling nonlinearity, exhibit varying strengths across architectures and lack a universally applicable “one-size-fits-all” solution. Single models often demonstrate unstable predictive performance across different datasets, making it difficult to ensure consistency in practical carbon market applications. Moreover, the majority of existing studies remain focused on point forecasting, with limited attention given to interval forecasting, thereby failing to effectively capture and convey the inherent uncertainty of carbon price fluctuations.

3. Production decision-making of a solo apparel firm under heterogeneous consumer sustainability preferences

3.1. Introduction

As discussed in Chapter 1 and 2, although prior studies have made notable contributions to production decision-making, several research gaps remain:

(1) While existing research acknowledges the presence of consumer heterogeneity, it has not integrated this factor into the production decision-making processes of apparel firms.

(2) Prior studies have primarily focused on identifying the determinants of consumers' environmental awareness, yet have paid insufficient attention to how such awareness influences the strategic behavior of apparel producers.

(3) The impact of carbon emission costs on production decisions has not been adequately addressed. In particular, there is a lack of systematic investigation into how carbon costs interact with willingness to pay and consumer environmental awareness to jointly shape firm behavior in the apparel sector.

Building upon prior research, this study aims to explore the following aspects:

(1) It fully incorporates consumer heterogeneity into the analysis of apparel firms' strategic behavior, examining its influence on production decisions.

(2) It reveals the transmission mechanism by which consumer environmental awareness affects the production side, and investigates

how firms adjust their production strategies in response to shifts in environmental consciousness.

(3) It introduces the factor of carbon emission costs and explores their interaction with willingness to pay and environmental awareness, assessing their impact on market share, pricing strategies, and profitability of apparel firms.

3.2 Model construction and hypotheses

3.2.1. Model assumptions

The proposed model is based on the following four key assumptions:

Assumption 1: The apparel firm is capable of producing both traditional and sustainable clothing. Their production strategies include producing both types of apparel simultaneously; producing only traditional apparel; producing only sustainable apparel; or choosing not to produce any type of apparel.

Assumption 2: Consumers make purchasing decisions based on the principle of utility maximization. Their choices include purchasing sustainable apparel; purchasing conventional apparel; or choosing not to purchase any apparel. In this study, traditional and sustainable apparel are assumed to be identical in terms of functionality, appearance, and comfort. The key distinction lies in environmental impact: sustainable apparel imposes significantly lower negative environmental externalities than traditional apparel. Moreover, consumer behavior is mutually exclusive, meaning each consumer selects only one product or opts out of purchasing.

Assumption 3: Consumers with environmental awareness tend to purchase sustainable apparel, as it offers them greater utility.

Assumption 4: Core firms in the apparel supply chain have incorporated carbon emissions into their pricing systems. It is assumed that producers of traditional apparel, due to their greater environmental impact, must include the carbon trading price in their utility function. In contrast, sustainable apparel producers, having less environmental impact, are not required to factor carbon trading prices into their utility functions. Furthermore, given that the production cost of sustainable apparel is higher, the market prices satisfy $P_c < P_s$, where P_c is the price of conventional apparel and P_s is the price of sustainable apparel.

For instance, H&M has integrated carbon trading prices into its supply chain, adjusting collaboration strategies based on carbon emissions and trading costs across upstream and downstream partners.

Following Chakraborty et al. (2021), the willingness to pay (WTP) for conventional apparel by an individual consumer, denoted as θ, is assumed to follow a uniform distribution over the interval $[0, \bar{\theta}]$, where $\bar{\theta}$ represents the maximum WTP. The average WTP across the consumer population is denoted by γ, and under a uniform distribution, we have $\gamma = \bar{\theta}/2$. A consumer's WTP for sustainable apparel is given by $(1+\delta)\theta$, where $\delta > 0$ represents the level of environmental awareness. The term $\delta\theta$ reflects the premium consumers are willing to pay for the environmental attributes of sustainable apparel.

Due to technological limitations, the unit production cost of sustainable apparel is higher than that of traditional apparel. Let $k > 1$ represent the cost coefficient. The relevant parameters are presented in Table 3.1, and the research framework of this study is illustrated in Fig. 3.1.

Table 3.1.

Description of symbols and parameters

Symbol	Meaning
U_c/U_s	Net utility from purchasing conventional/sustainable apparel
θ	WTP of an individual consumer for conventional apparel
γ	Average WTP of the consumer population for conventional apparel
δ	Consumer's level of environmental awareness
c	Unit production cost of conventional apparel
c_{ce}	Unit carbon emission cost of conventional apparel
k	Cost coefficient: sustainable apparel cost relative to conventional
q_c/q_s	Market share of conventional/sustainable apparel
p_c/p_s	Price of conventional/sustainable apparel
π	Profit of apparel firm

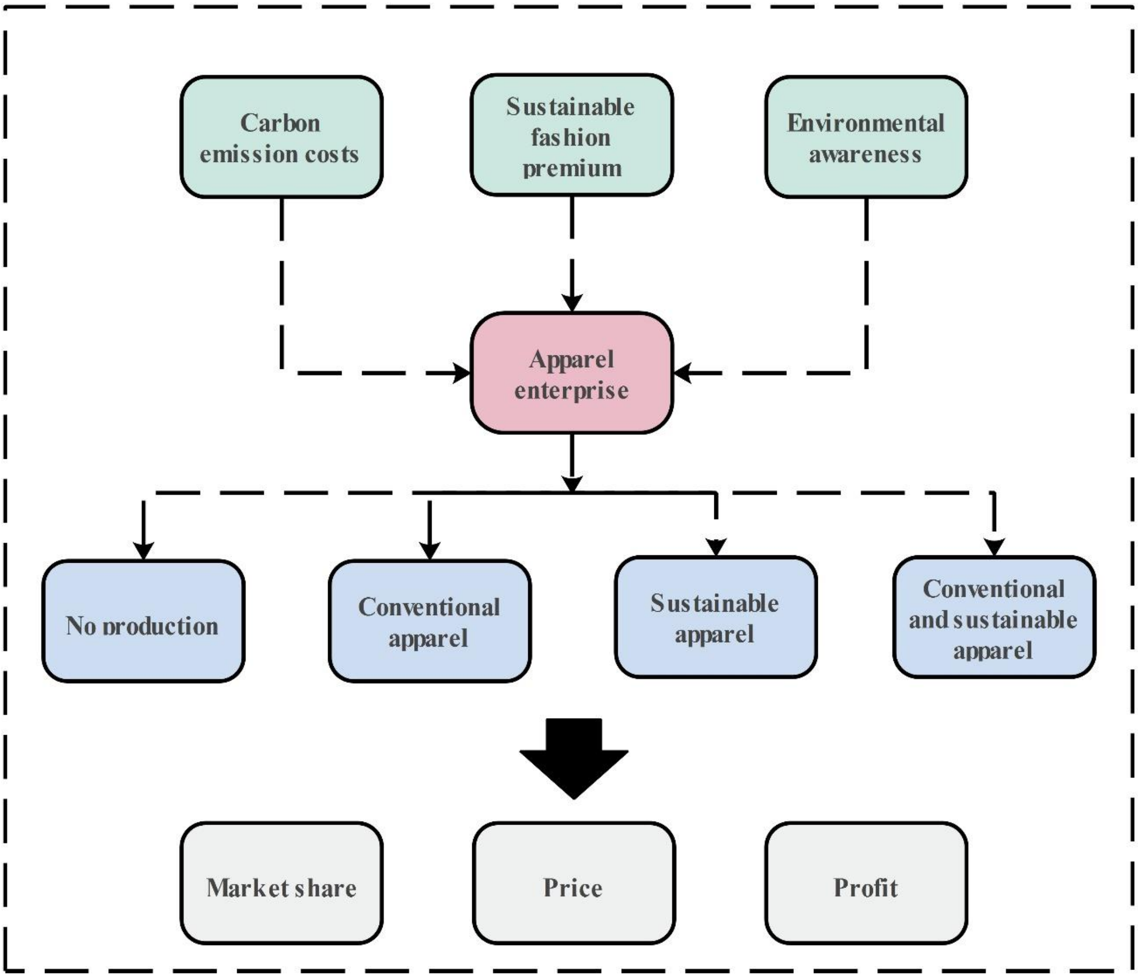


Fig. 3.1 Research framework

3.2.2. Decision model of apparel manufacturers

Referring to the framework proposed by Mussa and Sherwin (1978) this study defines the net utility functions for consumers purchasing conventional and sustainable apparel as follows:

$$U_c = \theta - p_c \tag{3.1}$$

$$U_s = (1+\delta)\theta - p_s \tag{3.2}$$

Based on the principle of utility maximization, consumer purchasing behavior can be classified into three distinct cases:

(1) Purchase sustainable apparel: when $U_s > U_c$ and $U_s > 0$, i.e., $\{\theta: U_s > U_c,\ U_s > 0\}$;

(2) Purchase conventional apparel: when $U_c > U_s$ and $U_c > 0$, i.e., $\{\theta: U_c > U_s,\ U_c > 0\}$;

(3) No purchase: when $U_c < 0$ and $U_s < 0$, i.e., $\{\theta: U_c < 0,\ U_s < 0\}$.

Threshold for purchasing conventional apparel: When $U_c > U_s$ and $U_c > 0$, consumers opt to purchase conventional apparel. Let θ_c be the threshold value for purchasing conventional apparel. Setting $U_c(\theta) = \theta - p_c = 0$, we obtain:

$$\theta_c = p_c \tag{3.3}$$

Threshold for purchasing sustainable apparel: When $U_s > U_c$ and $U_s > 0$, consumers choose sustainable apparel. Let θ_s be the threshold value for this choice. Setting $U_s(\theta) = U_s(\theta)$, we derive:

$$\theta_s = \frac{p_s - p_c}{\delta} \tag{3.4}$$

Demand functions for conventional and sustainable apparel are given by:

$$q_c = \int_{\theta_c}^{\theta_s} \frac{1}{\overline{\theta}} d\theta = \frac{\theta_s - \theta_c}{2\gamma} \tag{3.5}$$

$$q_s = \int_{\theta_s}^{\overline{\theta}} \frac{1}{\overline{\theta}} d\theta = \frac{2\gamma - \theta_s}{2\gamma} \tag{3.6}$$

At this point, the total profit maximization objective function for the apparel manufacturer producing both conventional and sustainable apparel are expressed as:

$$max_{p_s, p_c} \pi = (p_s - kc)q_s + (p_c - c - c_{ce})q_c \tag{3.7}$$

In Equation (3.7), p_s and p_c are the market prices of sustainable and conventional apparel, respectively, kc represents the unit production cost of sustainable apparel, and $c + c_{ce}$ is the total unit cost of conventional apparel, incorporating both production and carbon emission costs.

3.3. Production behavior of apparel manufacturers

3.3.1. Decision for apparel manufacturers

3.3.1.1. Conditions under firms opt not to produce

The apparel manufacturer aims to maximize profits by making production decisions based on consumer heterogeneity. Specifically, the average willingness to pay for conventional apparel (γ), consumer environmental awareness (δ), the unit production cost of conventional apparel (c), and its associated carbon emission cost (c_{cg}). By solving the profit maximization problem represented by Equation (7), the critical conditions for production and the corresponding equilibrium outcomes are derived.

From Equations (5)–(6), market demands for the two types of apparel are

$$q_s = \frac{2\gamma-\theta_s}{2\gamma} \text{ and } q_c = \frac{\theta_s-\theta_c}{2\gamma},$$

where

$$\theta_s = \frac{p_s-p_c}{\delta} \text{ and } \theta_c = p_c.$$

Thus it follows:

$$\begin{cases} q_s = 1 - \dfrac{p_s - p_c}{2\gamma\delta} \\ q_c = \dfrac{p_s - p_c - \delta p_c}{2\gamma\delta} \end{cases}$$

To maximize the function $max_{p_s,p_c}\pi = (p_s - kc)\left(1 - \frac{p_s - p_c}{2\gamma\delta}\right) + (p_c - c - c_{ce})\left(\frac{p_s - p_c - \delta p_c}{2\gamma\delta}\right)$, we take the partial derivatives with respect to p_s and p_c and set them equal to zero. This yields:

$$\begin{cases} p_s = \gamma(1+\delta) + \dfrac{kc}{2} \\ p_c = \gamma + \dfrac{c + c_g}{2} \end{cases}$$

The firm won't produce if profit at optimal prices is non-positive:

$$p_c^* \leq c + c_{ce} \text{ and } p_s^* \leq kc$$

Thus:

$$\begin{cases} \gamma \leq \dfrac{c + c_{ce}}{2} \\ \gamma \leq \dfrac{kc}{2(1+\delta)} \end{cases}$$

In addition, it holds $q_c^* \leq 0$ and $q_s^* \leq 0$. This yields the following conditions:

$$\gamma \leq \frac{kc - c - c_{ce}}{2\delta}$$

$$kc < (1+\delta)(c + c_{ce})$$

Therefore, the condition under which the firm chooses not to produce is $\gamma \leq min\left\{\frac{kc}{2(1+\delta)}, \frac{c+c_{ce}}{2}, \frac{kc-c-c_{ce}}{2\delta}\right\}$ with cost constraint $c + c_{ce} < kc < (1+\delta)(c + c_{ce})$.

At this point, consumers' willingness to pay is insufficient, making it unprofitable for the apparel firm to operate. As a result, the firm chooses to exit the market or cease production.

3.3.1.2. Conditions for apparel firms to exclusively produce conventional apparel

For the apparel firm's decision to produce only conventional apparel, the following conditions must be simultaneously satisfied: the production of conventional apparel yields positive profits, while the production of sustainable apparel fails to generate positive returns.

From the profit-maximizing solutions one obtains:

$$p_c^* = \gamma + \frac{c+c_{ce}}{2},\ \ p_s^* = \gamma(1+\delta) + \frac{kc}{2}$$

To ensure positive demand for conventional apparel the following conditions must be satisfied:

$$\begin{cases} q_c^* > 0 \\ p_c^* \geq c + c_{ce} \end{cases}$$

Thus:

$$\begin{cases} \gamma \leq \dfrac{kc - c - c_{ce}}{2\delta} \\ \gamma > \dfrac{c + c_{ce}}{2} \end{cases}$$

The demand for sustainable apparel is non-positive and its price is lower than its cost:

$$\begin{cases} q_s^* \leq 0 \\ p_s^* \leq kc \end{cases}$$

Thus:

$$\begin{cases} \gamma \leq \dfrac{kc - c - c_{ce}}{2\delta} \\ \gamma \leq \dfrac{kc}{2(1+\delta)} \end{cases}$$

Therefore, the conditions under which a firm chooses to exclusively produce conventional apparel are

$$\frac{c + c_{ce}}{2} < \gamma \leq min\left\{\frac{kc - c - c_{ce}}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$$

and $kc > (1+\delta)c + (1+\delta)c_{ce}$.

At this stage, when the production cost of sustainable apparel is excessively high and consumer willingness to pay is confined to a specific range, the market will spontaneously settle into an equilibrium in which traditional apparel dominates.

3.3.1.3. Conditions for apparel firms to exclusively produce sustainable apparel

For a apparel firm to choose to exclusively produce sustainable apparels, two conditions must be simultaneously satisfied: producing conventional apparels does not yield positive profit, whereas producing sustainable apparels does.

To ensure negative demand for conventional apparels:

$$q_g^* = \frac{kc-(1+\delta)(c+c_g)}{4\gamma\delta} < 0 \text{ and } p_g^* < c + c_g \to \gamma < \frac{c+c_g}{2}$$

To ensure non-negative demand for sustainable apparels:

$$q_e^* = 1 - \frac{p_e - p_g}{2\gamma\delta} \geq 0$$

$$2\gamma\delta \geq \gamma\delta + \frac{kc - c - c_g}{2} \to \gamma \geq \frac{kc - c - c_g}{2\delta}$$

$$p_e^* \geq kc$$

$$\gamma \geq \frac{kc}{2(1+\delta)}$$

Therefore, the conditions under which the firm chooses to exclusively produce sustainable apparels are:

$$max\left\{\frac{kc-c-c_g}{2\delta},\frac{kc}{2(1+\delta)}\right\} \leq \gamma < \frac{c+c_g}{2}$$

$$\text{and } kc < (1+\delta)c + (1+\delta)c_g$$

$\frac{kc-c-c_g}{2\delta} \leq \gamma$ ensures that the price advantage of conventional apparels is not fully neutralized by environmental awareness. If γ is too low, all consumers will switch to sustainable apparels.

$\frac{kc}{2(1+\delta)} \leq \gamma$ ensures that the WTP for conventional apparels is not lower than half the cost of sustainable apparels (adjusted for environmental awareness), preventing unsustainable price-based substitution.

$\gamma < \frac{c+c_g}{2}$ ensures that consumer willingness to pay for conventional apparels remains below half of their total cost.

$kc < (1+\delta)c + (1+\delta)c_g$ implies that the production cost of sustainable apparels must remain lower than the environmentally adjusted cost of conventional apparels. Otherwise, sustainable products become economically unacceptable to consumers.

In this scenario, when the production cost of sustainable apparels is lower than the adjusted cost of conventional apparels, and consumer willingness to pay for conventional apparels is compressed within a specific interval, the market will naturally reach an equilibrium in which sustainable apparels fully replace conventional ones.

3.3.1.4. Conditions for apparel firms to produce both conventional and sustainable apparels

For the apparel firm's decision to produce both traditional and sustainable apparel simultaneously, the following conditions must be satisfied.

The demand for both types of apparel must be positive:

$$\begin{cases} q_c^* > 0 \\ p_c^* > c + c_{ce} \end{cases}$$

This implies:

$$\gamma > \frac{c + c_{ce}}{2}$$

To ensure positive demand for sustainable apparel, the following must be satisfied:

$$\begin{cases} q_s^* \geq 0 \\ p_s^* \geq kc \end{cases}$$

This implies:

$$\gamma > \frac{kc}{2(1+\delta)}$$

Therefore, the conditions under which a firm chooses to produce both conventional and sustainable apparel are

$\gamma > max\left\{\frac{c+c_{ce}}{2}, \frac{kc-c-c_{ce}}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$ and $kc > (1+\delta)c + (1+\delta)c_{ce}$.

In this scenario, when consumer willingness to pay is sufficiently high to cover both the profitability threshold of conventional apparel and the environmental premium of sustainable apparel—and when the cost of sustainable apparel is significantly higher than that of environmentally adjusted conventional apparel—the market naturally reaches an equilibrium where both product types coexist.

3.3.2. Revenue analysis of apparel firms

3.3.2.1. Revenue analysis under exclusive production of conventional apparels

When the apparel firm chooses to exclusively produce conventional apparel, the following conditions must be satisfied:

● The utility of conventional apparel dominates: $U_c > U_s$ and $U_c > 0$.

● The threshold value θ_c for consumers purchasing conventional apparel satisfies:

$$\theta_c = p_c$$

● The threshold value θ_s for consumers purchasing sustainable apparel satisfies:

$$\theta_s = \frac{p_s - p_c}{\delta}$$

In addition, due to the relatively higher price of sustainable apparel, the threshold θ_s is given by $\theta_s = 2\gamma$. Under this scenario and based on Equation (5), the market share of conventional apparel is:

$$q_c = \frac{2\gamma - \theta_c}{2\gamma} = \frac{2\gamma - p_c}{2\gamma} = 1 - \frac{p_c}{2\gamma}$$

The profit function is:

$$\pi = (p_c - c - c_{ce})q_c = (p_c - c - c_{ce})\left(1 - \frac{p_c}{2\gamma}\right)$$

Next, we take the derivative of π with respect to p_c and set it equal to zero:

$$\frac{d\pi}{dp_c} = \left(1 - \frac{p_c}{2\gamma}\right) + (p_c - c - c_{ce})\left(-\frac{1}{2\gamma}\right) = 0$$

This leads to:

$$p_c^* = \gamma + \frac{c + c_{ce}}{2}$$

Substituting $p_c^* = \gamma + \frac{c+c_{ce}}{2}$ in $q_c = 1 - \frac{p_c}{2\gamma}$, we obtain the market share of conventional apparel as follows:

$$q_c^* = \frac{2\gamma - c - c_{ce}}{4\gamma}$$

Inserting p_c^* and q_c^* into $\pi = (p_c - c - c_{ce})\left(1 - \frac{p_c}{2\gamma}\right)$, the optimal profit is obtained as follows:

$$\pi^* = \frac{(2\gamma - c - c_{ce})^2}{8\gamma}$$

3.3.2.2. Revenue analysis under exclusive production of sustainable apparels

When the apparel firm chooses to exclusively produce sustainable apparel, the following conditions must be satisfied:

● The utility of sustainable apparel dominates: $U_c > U_s$ and $U_s \geq 0$;

●The threshold for consumer purchase satisfies:

$$\theta \geq \frac{p_s}{1+\delta}.$$

● The purchase threshold for sustainable apparel satisfies:

$$\theta_s = \frac{p_s}{1+\delta}$$

The result of the market share of sustainable apparel is:

$$q_s = 1 - \frac{p_s}{2\gamma(1+\delta)}$$

The firm’s profit function can be expressed as:

$$\pi = (p_s - kc)q_s = (p_s - kc)\left(1 - \frac{p_s}{2\gamma(1+\delta)}\right)$$

Following the same approach as in Section 4.2.1, taking the derivative of π with respect to p_s and setting it to zero yields the optimal price:

$$p_s^* = \gamma(1+\delta) + \frac{kc}{2}$$

The corresponding optimal market share of sustainable apparel is:

$$q_s^* = \frac{2\gamma(1+\delta) - kc}{4\gamma(1+\delta)}$$

The optimal profit is:

$$\pi^* = \frac{[2\gamma(1+\delta) - kc]^2}{8\gamma(1+\delta)}$$

3.3.2.3 Revenue analysis under mixed production of conventional and sustainable apparels

Under a mixed production strategy, the firm supplies both conventional and sustainable apparel, and consumers make choices based on utility maximization. The market equilibrium requires that:

● Both products have positive demand.

● The firm maximizes profit through price optimization.

Accordingly, the consumer threshold for purchasing conventional apparel is given by:

$$\theta_C = p_C$$

The threshold for purchasing sustainable apparel is:

$$\theta_S = \frac{p_S - p_C}{\delta}$$

For the market share of conventional apparel, corresponding to consumers with preference $\theta \epsilon [\theta_c, \theta_s]$ is:

$$q_c = \frac{\theta_s - \theta_c}{2\gamma} = \frac{p_s - (1+\delta)p_c}{2\gamma\delta}$$

For the market share of sustainable apparel, corresponding to consumers with $\theta \epsilon [\theta_s, 2\gamma]$ is:

$$q_s = \frac{2\gamma - \theta_s}{2\gamma} = \frac{2\gamma\delta - p_s + p_c}{2\gamma\delta}$$

The firm's total profit function is given by:

$$\pi = (p_c - c - c_{ce})\frac{p_s - (1+\delta)p_c}{2\gamma\delta} + (p_s - kc)\frac{2\gamma\delta - p_s + p_c}{2\gamma\delta}$$

Taking the partial derivatives of π with respect to p_c and p_s, and setting them to zero yields the following optimal prices:

$$\begin{cases} p_c^* = \gamma + \dfrac{c + c_{ce}}{2} \\ p_s^* = \gamma(1+\delta) + \dfrac{kc}{2} \end{cases}$$

The corresponding equilibrium market shares are:

$$\begin{cases} q_c^* = \dfrac{kc - (1+\delta)(c + c_{ce})}{4\gamma\delta} \\ q_s^* = \dfrac{2\gamma\delta + c + c_{ce} - kc}{4\gamma\delta} \end{cases}$$

Finally, the equilibrium profit is given by:

$$\pi^* = -\frac{kc}{2} - \frac{kc(c + ce)}{4\gamma\delta} + \frac{(1+\delta)(c + c_{ce})^2 + k^2c^2}{8\gamma\delta} + \frac{\gamma(1+\delta)}{2}$$

3.3.3. Summary of strategic behaviors of apparel manufacturers

To comprehensively capture the decision-making logic of apparel firms in response to varying market and policy conditions, we summarize the key findings of the model through a series of formal propositions. These propositions delineate the threshold conditions under which different production strategies are adopted and clarify how crucial factors such as consumers' average willingness to pay, environmental awareness and carbon emission costs jointly determine pricing, market shares and profitability. These propositions provide an analytically tractable framework that supports strategic decision-making for firms operating under heterogeneous consumer preferences and evolving carbon pricing policies.

Proposition 1: Under different levels of consumers' average willingness to pay γ, the threshold conditions for apparel production decisions are as follows:

(1) When $\gamma \leq min\left\{\frac{kc}{2(1+\delta)}, \frac{c+c_g}{2}, \frac{kc-c-c_g}{2\delta}\right\}$ and $c + c_g < kc < (1+\delta)\left(c + c_g\right)$, the apparel firm chooses not to produce.

(2) When $\frac{c+c_g}{2} < \gamma \leq min\left\{\frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$and $kc > (1+\delta)c + (1+\delta)c_g$, the apparel firm chooses to produce only conventional apparel.

(3) When $max\left\{\frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\} \leq \gamma < \frac{c+c_g}{2}$ and $kc < (1+\delta)c + (1+\delta)c_g$, the apparel firm chooses to produce only sustainable apparel.

(4) When $\gamma > max\left\{\frac{c+c_g}{2}, \frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$ and $kc > (1+\delta)c + (1+\delta)c_g$, the apparel firm chooses to produce both conventional and sustainable apparel.

Proposition 2: The firm's equilibrium outcomes under different production decisions are summarized as follows:

(1) If producing only conventional apparel:

$$p_g^* = \gamma + \frac{c+c_g}{2}, \quad q_g^* = \frac{2\gamma-c-c_g}{4\gamma}, \quad \pi^* = \frac{\left(2\gamma-c-c_g\right)^2}{8\gamma}$$

(2) If producing only sustainable apparel:

$$p_e^* = \gamma(1+\delta) + \frac{kc}{2}, \quad q_e^* = \frac{2\gamma(1+\delta)-kc}{4\gamma(1+\delta)}, \quad \pi^* = \frac{[2\gamma(1+\delta)-kc]^2}{8\gamma(1+\delta)}$$

(3) If producing both sustainable and conventional apparel:

$$p_g^* = \gamma + \frac{c+c_g}{2}, \quad q_g^* = \frac{kc-(1+\delta)\left(c+c_g\right)}{4\gamma\delta}$$

$$p_e^* = \gamma(1+\delta) + \frac{kc}{2}, \quad q_e^* = \frac{2\gamma\delta+c+c_g-kc}{4\gamma\delta}$$

$$\pi^* = -\frac{kc}{2} - \frac{kc(c+c_g)}{4\gamma\delta} + \frac{(1+\delta)(c+c_g)^2 + k^2c^2}{8\gamma\delta} + \frac{\gamma(1+\delta)}{2}$$

Propositions 1 and 2 collectively address the core production strategy problem faced by apparel firms: what to produce, how to produce, how to price, and how much profit to expect. In particular, $\gamma \leq min\left\{\frac{kc}{2(1+\delta)}, \frac{c+c_g}{2}, \frac{kc-c-c_g}{2\delta}\right\}$ serves as the threshold that determines whether the firm proceeds with production. In other words, production is justified only when the consumer's willingness to pay exceeds either the total production costs or the cost differential, adjusted for environmental awareness.

Proposition 3: When the apparel firm produces only conventional apparel, the price and market share of conventional apparel are positively correlated with the average consumer willingness to pay γ:

- $\frac{\partial p_c^*}{\partial \gamma} = 1$: This implies that the firm fully transfers increases in willingness to pay into price increments.
- $\frac{\partial q_c^*}{\partial \gamma} = \frac{c+c_{ce}}{4\gamma^2} > 0$: This indicates that an increase in γ raises the market share of conventional apparel, though at a decreasing rate.
- $\frac{\partial \pi^*}{\partial \gamma} = \frac{1}{2} - \frac{(c+c_{ce})^2}{8\gamma^2}$: This implies that profits increase with γ, when $\gamma > \frac{c+c_g}{2}$; otherwise, profits may decline.

When the firm produces only sustainable apparel, both the price and market share of sustainable apparel are positively correlated with the average willingness to pay for conventional apparel γ:

- $\frac{\partial p_s^*}{\partial \gamma} = 1 + \delta$: This indicates that both willingness to pay and environmental awareness jointly contribute to higher sustainable apparel pricing.
- $\frac{\partial q_s^*}{\partial \gamma} = \frac{kc}{4(1+\delta)\gamma^2} > 0$: An increase in γ raises the market share of sustainable apparel, but the rate of increase diminishes.
- $\frac{\partial \pi^*}{\partial \gamma} = \frac{1+\delta}{2} - \frac{k^2c^2}{8(1+\delta)\gamma^2}$: Profit increases with γ when $\gamma > \frac{kc}{2(1+\delta)}$; otherwise, it may decline.

In the mixed production case, sustainable apparel price, conventional apparel price, and the market share of sustainable apparel are positively correlated with γ, while the market share of conventional apparel is negatively correlated with γ. Taking the partial derivatives of p_s^*, p_c^*, q_s^* and q_c^* with respect to γ yields the following results:

$$\frac{\partial p_s^*}{\partial \gamma} > 0, \frac{\partial p_c^*}{\partial \gamma} > 0, \frac{\partial q_s^*}{\partial \gamma} > 0, \frac{\partial q_c^*}{\partial \gamma} < 0$$

$\frac{\partial q_e^*}{\partial \gamma} > 0$, $\frac{\partial q_g^*}{\partial \gamma} < 0$ .This outcome arises because, with higher γ, firms raise the price of conventional apparel. Due to substitution effects, some price-sensitive or environmentally conscious consumers shift from conventional to sustainable apparel. This results in a reallocation of market share—an increasing for sustainable apparel and decreasing for conventional ones—a dynamic that resembles the behavior of Giffen goods.

Proposition 4: When the firm produces only conventional apparel, the price of conventional apparel is positively correlated with the carbon emission cost c_{ce}, while the market share is negatively correlated with c_{ce}.

● $\frac{\partial p_c^*}{\partial c_{ce}} = \frac{1}{2}$: This implies that the firm passes 50% of the carbon cost to consumers, while absorbing the other half.

● $\frac{\partial q_c^*}{\partial c_{ce}} = -\frac{1}{4\gamma}$: This indicates that carbon costs reduce the market share of conventional apparel.

In the mixed production case, the price of conventional apparel and the market share of sustainable apparel are positively correlated with c_{ce}, while the market share of conventional apparel is negatively correlated with c_{ce}:

● $\frac{\partial p_c^*}{\partial c_{ce}} = \frac{1}{2}$: The firm still transfers 50% of the carbon cost to consumers.

● $\frac{\partial q_s^*}{\partial c_{ce}} = \frac{1}{4\gamma\delta}$: Carbon pricing boosts demand for sustainable apparel.

● $\frac{\partial q_c^*}{\partial c_{ce}} = -\frac{1+\delta}{4\gamma\delta}$: Carbon costs undermine the market share of conventional apparel.

Proposition 5: When the firm produces only sustainable apparel, both the price and market share of sustainable apparel are positively correlated with environmental awareness δ.

- $\frac{\partial p_s^*}{\partial \delta} = \gamma$: This indicates that firms leverage environmental awareness to raise prices, and the markup is directly proportional to the baseline willingness to pay γ.
- $\frac{\partial q_s^*}{\partial \delta} = -\frac{kc}{4\gamma(1+\delta)^2}$: While increasing δ improves market share, the growth rate diminishes as awareness rises.

In the mixed production scenario, both the price and market share of sustainable apparel are positively correlated with δ, whereas the market share of conventional apparel is negatively correlated with δ.

- $\frac{\partial p_s^*}{\partial \delta} = \gamma$: Environmental awareness directly increases the price of sustainable apparel.
- $\frac{\partial q_s^*}{\partial \delta} = \frac{kc-c-c_g}{4\gamma\delta}$: Increased environmental awareness stimulates demand for sustainable apparel.
- $\frac{\partial q_c^*}{\partial \delta} = -\frac{kc}{4\gamma\delta^2}$: Environmental awareness reduces the market share of conventional apparel, with the rate of decline accelerating as δ increases.

3.4. **Empirical analysis**

To further investigate the impact of carbon emission cost c_g and consumer environmental awareness δ on apparel manufacturers under different scenarios, this study conducts an empirical analysis based on the framework established by Chakraborty et al. (2021), while incorporating realistic parameter settings reflecting current market conditions. This approach allows for a more intuitive and visual understanding of how c_{ce} and δ influence market shares, apparel prices, and firm profits in the apparel industry. The relevant parameter values are presented in Table 3.2.

Table 3.2

Model parameter values

Parameter	γ	c	k
Value	100	20	1.5

3.4.1. Impact of carbon emission costs on apparel firms

3.4.1.1. Impact of carbon emission costs on firms exclusively producing conventional apparels

In Fig. 3.2, panels (a), (b) and (c) illustrate the impact of carbon emission costs on the market share, pricing and profitability of traditional apparel producers, respectively, with carbon emission cost ranging from 0 to 180.

Specifically, Fig. 3.2(a) presents the linear crowding-out effect of carbon emission costs on the market share of traditional apparel. As carbon costs increase, the market share steadily declines and eventually drops to zero at a critical point, indicating that the firm is entirely pushed out of the market. This reflects how rising carbon costs significantly compress the survival space of traditional apparel firms, thereby driving structural transformation of the industry toward a low-carbon model.

Fig. 3.2(b) illustrates the influence of carbon costs on pricing strategies. When faced with increasing carbon emission costs, firms partially pass these costs on to consumers, resulting in higher market prices. The orange price curve rises with a slope of 0.5, indicating that the firm is able to pass only 50% of the carbon cost to consumers, while the remaining portion must be absorbed internally. The gray dashed line represents the total cost curve, which increases proportionally with carbon costs. This highlights the firm's limited ability to fully pass on carbon costs due to competitive pressure, thereby squeezing profit margins and influencing pricing decisions.

Fig. 3.2(c) shows the non-linear decline in profits as carbon costs rise. The figure indicates that profit is non-linearly sensitive to carbon emission costs: as carbon emission costs increase, the profitability of traditional apparel firms drops sharply, revealing a high vulnerability of profit performance to environmental cost pressures.

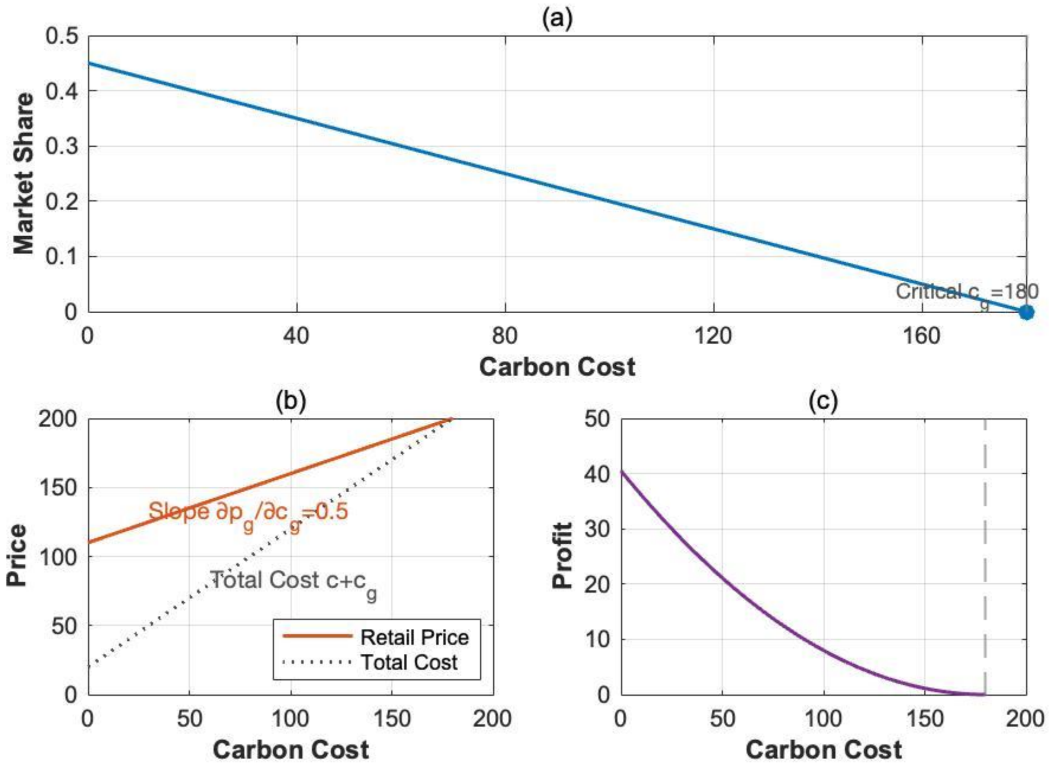


Fig. 3.2. Impact of carbon emission cost on firms exclusively producing traditional apparel

3.4.1.2. Impact of carbon emission cost on firms producing both conventional and sustainable apparels

In Fig. 3.3, panels (a), (b) and (c) depict the impact of carbon emission costs on the market share, pricing and profitability of traditional and sustainable apparel producers, respectively.

Fig. 3.3(a) illustrates the substitution effect of carbon emission costs on market shares. As carbon costs exert increasing pressure on traditional apparel, a substitution effect emerges: the market share of sustainable apparel gradually rises. At the point where the market share of traditional apparel reaches its lowest level, the market share of sustainable apparel peaks, indicating a shift in consumer preference driven by environmental cost considerations.

Fig. 3.3(b) presents the effect of carbon costs on firms' pricing strategies. The total market cost increases linearly with a slope of 1. The pricing curve for traditional apparel rises with a slope of 0.5, indicating that traditional apparel firms are able to pass only 50% of the carbon cost onto consumers. In contrast, the slope of the sustainable apparel pricing curve remains flat at 0, demonstrating that the price of sustainable apparel is unaffected by carbon emission costs, thus giving it a relative pricing advantage in carbon-constrained markets.

Fig. 3.3(c) shows the contrasting nonlinear trends in profit. As carbon costs increase, the profits of traditional apparel producers decline nonlinearly, reflecting their growing vulnerability to environmental cost pressures. Conversely, the profits of sustainable apparel firms increase nonlinearly, benefiting from the rising market preference and relative cost stability, which enhance their competitive edge and profitability under stricter carbon regulation.

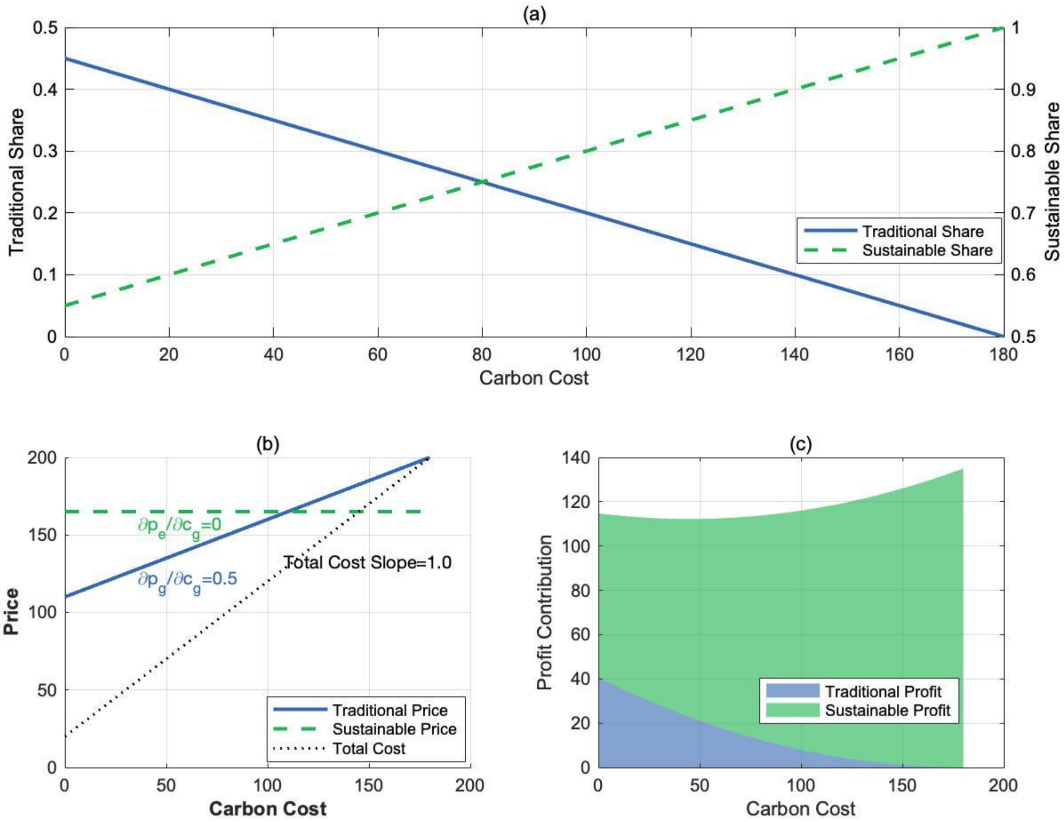


Fig 3.3. Impact of carbon emission cost on firms producing both traditional and sustainable apparel

3.4.2. Impact of consumer environmental awareness on apparel firms

3.4.2.1. Impact of consumer environmental awareness on firms exclusively producing sustainable apparels

In Fig. 3.4, panels (a), (b) and (c) illustrate the impact of consumer environmental awareness on the market share, pricing and profitability of sustainable apparel producers, respectively, with environmental awareness ranging from 0.1 to 0.5.

Specifically, Fig. 3.4(a) shows that as consumers' environmental awareness increases, they are more willing to pay for "sustainability attributes." This shift in preference leads more consumers to choose sustainable apparel, resulting in a rising market share.

Fig. 3.4(b) demonstrates a positive correlation between product price and environmental awareness. As consumer environmental awareness increases, their tolerance for paying a sustainability premium also rises. This enables firms to set higher prices without experiencing significant loss in demand.

Fig. 3.4(c) depicts the upward trend in profitability as environmental awareness increases. With greater willingness to pay for sustainability, firms can charge higher prices while maintaining or even expanding their customer base. Within a certain range, this significantly boosts the profitability of sustainable apparel producers.

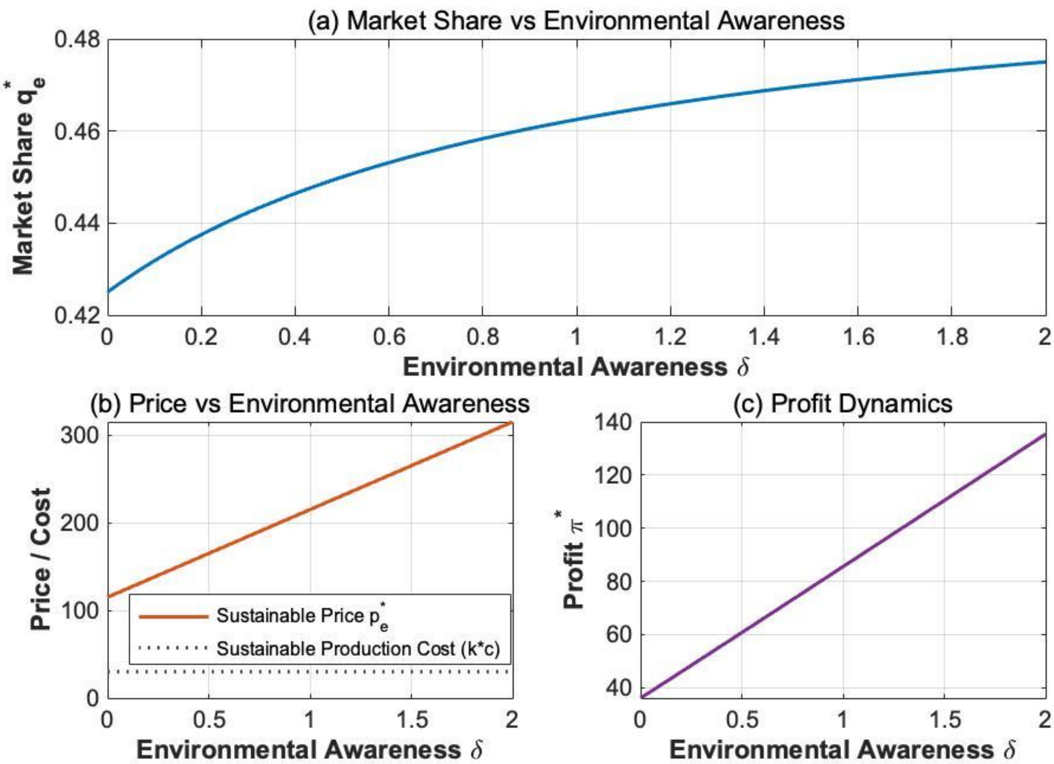


Fig 3.4. Impact of consumer environmental awareness on the firm exclusively producing sustainable apparel

3.4.2.2. Impact of consumer environmental awareness on firms producing both conventional and sustainable apparels

In Fig. 3.5, panels (a), (b) and (c) illustrate the impact of consumer environmental awareness on the market share, pricing and profitability of both traditional and sustainable apparel producers, respectively.

Specifically, Fig. 3.5(a) demonstrates the substitution effect of environmental awareness on market shares. As consumer environmental awareness increases, the market share of sustainable apparel gradually expands, while the share of traditional apparel steadily declines. This reflects a shift in consumer preference driven by heightened environmental concern.

Fig. 3.5(b) presents the influence of environmental awareness on pricing strategies. In the mixed production model, consumer environmental awareness only affects the perceived value of sustainable apparel. As a result, the optimal price of traditional apparel remains unaffected by changes in environmental awareness. In contrast, the willingness of consumers to pay for the sustainability attributes of sustainable apparel increases with higher environmental awareness, enabling firms to raise prices without significantly reducing demand. Consequently, the premium of sustainable apparel over traditional apparel widens as environmental awareness grows.

Fig. 3.5(c) shows how firms derive profits from both product lines. On the one hand, the price of traditional apparel remains stable, but its demand may decline as consumers become more environmentally conscious. On the other hand, both the price and demand for sustainable apparel may increase with rising environmental awareness. When environmental awareness is low, the environmental advantage of sustainable apparel is less compelling, resulting in a smaller market share and firms relying primarily on traditional apparel for profit. As environmental awareness increases, both demand and pricing power for sustainable apparel improve, leading to a growing contribution of sustainable apparel to overall firm profitability.

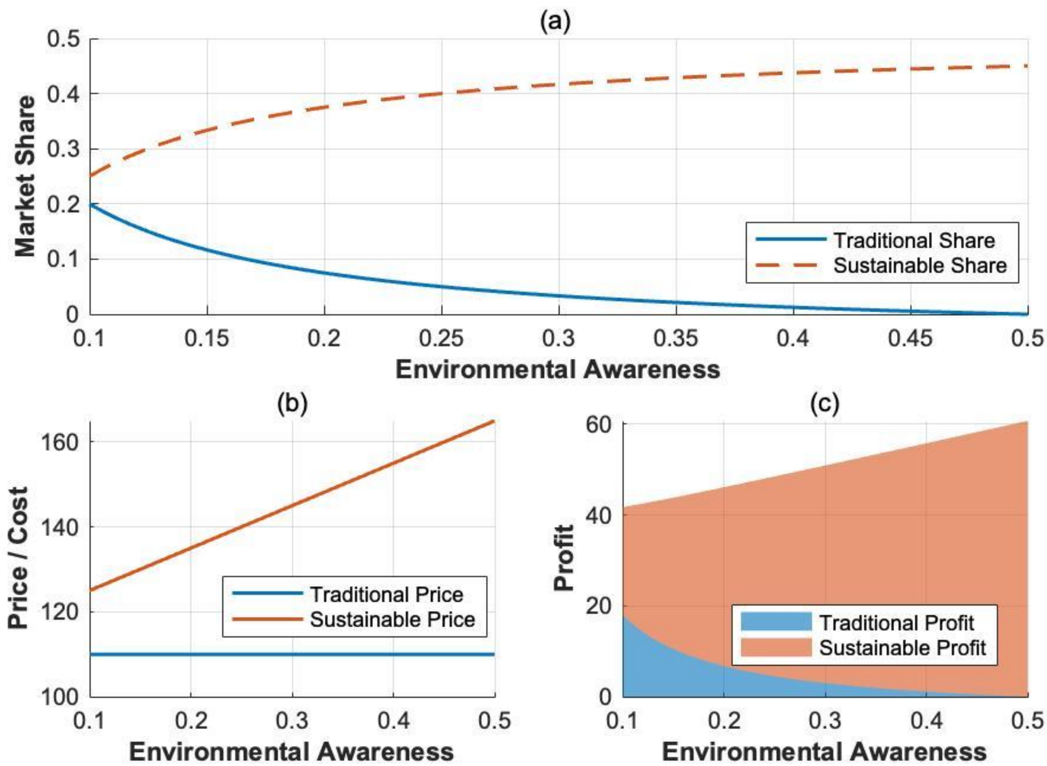


Fig 3.5. Impact of consumer environmental awareness on the firm producing both traditional and sustainable apparel

3.5. Summary

3.5.1. Research conclusions

Based on heterogeneous consumer preferences, this study develops a production decision model for apparel firms that incorporates both carbon emission costs and environmental awareness. It systematically analyzes firms' production strategies, pricing behavior, and profit dynamics under varying market conditions. The key findings are as follows:

(1) Production strategies of apparel firms are highly dependent on the dynamic balance between the average consumer's willingness to pay and cost structure.

● When consumer willingness to pay is relatively low, i.e.,$\gamma \leq min\left\{\frac{kc}{2(1+\delta)}, \frac{c+c_g}{2}, \frac{kc-c-c_g}{2\delta}\right\}$, and the cost of sustainable apparel is high, $c + c_g < kc < (1 + \delta)\left(c + c_g\right)$, the firm chooses a non-production strategy.

● When willingness to pay is moderate, $\frac{c+c_g}{2} < \gamma \leq min\left\{\frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$, and the cost of sustainable apparel is significantly higher, $kc > (1 + \delta)c + (1 + \delta)c_g$, the firm adopts a conventional-only production strategy.

● When willingness to pay is relatively high, but the cost advantage of conventional apparel is limited, $max\left\{\frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\} \leq \gamma < \frac{c+c_g}{2}$,and sustainable apparel are relatively low-cost, $kc < (1 + \delta)c + (1 + \delta)c_g$, the firm switches to sustainable-only production.

● When willingness to pay is sufficiently high, $\gamma > max\left\{\frac{c+c_g}{2}, \frac{kc-c-c_g}{2\delta}, \frac{kc}{2(1+\delta)}\right\}$, and sustainable apparel have significant cost advantages, $kc > (1+\delta)c + (1+\delta)c_g$, the firm adopts a mixed production strategy.

(2) Carbon emission costs play a key role in driving industry transformation.

Rising carbon emission costs compress the profit margins of the traditional apparel firm, leading to a gradual decline in their market share and accelerating the industry's transition toward low-carbon production.

(3) Consumer environmental awareness reshapes market structure. Increased environmental awareness widens the price premium between sustainable and traditional apparel and drives the shift of market share toward sustainable products.

3.5.2. Policy recommendations

To promote sustainable transformation in the apparel industry, the following policy measures are recommended:

(1) Increase carbon emission costs in stages. Governments should gradually raise carbon taxes or tighten carbon quotas to force firms to improve production processes or adopt low-carbon materials. Additionally, differentiated carbon pricing could be implemented—imposing higher carbon taxes on high-pollution fibers while offering exemptions or incentives for recycled fibers—to encourage upstream supply chain reform.

(2) Reduce the cost of sustainable apparel. Governments can promote industrial upgrading by subsidizing the development and scaling of sustainable technologies. This could include funding low-carbon innovations through green innovation funds or offering tax credits to incentivize the adoption of clean energy by apparel manufacturers.

(3) Enhance consumer environmental awareness to expand market demand. Introduce a carbon labeling system requiring official certification for sustainable apparel to build consumer trust. At the same time, promote sustainable fashion through public campaigns and social media, and offer incentives such as personal income tax deductions or green consumption vouchers to consumers who purchase sustainable apparel.

4. Carbon price interval forecasting: A hybrid deep learning methodology to support sustainable production decisions

4.1. Introduction

As global climate change is an increasingly pressing issue, reducing carbon emissions has become a global priority (Xu and Salem, 2021; Han et al., 2025). The carbon trading market is one of the key mechanisms to reduce emissions (Lin and Zhang, 2022; Cao et al., 2023; Jiang et al., 2025). Therefore, China launched pilot carbon trading markets in 2013 (Hao et al., 2020; Bai et al., 2024). However, due to the non-linearity and non-stationarity of carbon prices, accurate prediction remains a crucial challenge (Lovcha et al., 2022; Qin et al., 2024).

Earlier research has mainly emphasized point prediction, which generate deterministic predictions and fail to account for uncertainty (Wang et al., 2022; Yang et al., 2022). In contrast, interval prediction addresses this limitation by quantifying uncertainty through the estimation of lower and upper bounds of predicted values (Tian and Hao, 2020; Zeng et al., 2024). A critical aspect of interval prediction is the selection of an appropriate interval construction method. To this end, scholars have explored various strategies for interval construction. One commonly used approach constructs PIs from point prediction using Error distribution methods. This method is based on the assumption that the errors associated with point prediction follow a known probability distribution and derives the interval by determining the upper and lower bounds of the errors at a given confidence level. However, in real-world scenarios, the error distribution often fails to satisfy such strict assumptions (Marín et al., 2019; Gao and Shao, 2022; Johannssen et al., 2022). To overcome this limitation, kernel density estimation (KDE), which avoids assumptions about the underlying distribution, has been widely adopted (Katkovnik and Shmulevich, 2002; Yu et al., 2023). Despite its advantage, KDE can suffer from instability due to its sensitivity to bandwidth selection. Moreover, the fixed interval boundaries derived from KDE cannot dynamically reflect local data characteristics (Wang et al., 2024; Sha et al., 2025).

To address this issue, quantile regression (QR) has been introduced for interval prediction. It directly learns the conditional quantiles of the target variable, enabling dynamic adjustment and flexible adaptation of PI boundaries. Compared to Error distribution method and KDE, QR demonstrates superior predictive accuracy. However, it lacks effective constraints on interval width, potentially leading to overly wide intervals and diminishing their practical interpretability and credibility (Ji et al., 2025). Recently, the scaling approach (SA) has emerged as a promising alternative for constructing PIs. This method scales the target variable to obtain interval-valued labels and constructs PIs using machine learning models. By incorporating multi-objective optimization algorithms, the model simultaneously balances prediction accuracy and interval width, thereby minimizing interval range, ensuring reliability, and enhancing predictive efficiency and practical utility (Wang et al., 2023). However, SA still faces several limitations. First, previous studies often assume symmetric scaling factors for the upper and lower bounds, whereas real-world data may be asymmetric. Second, traditional multi-objective optimization algorithms typically employ a fixed crossover probability, which may impair global search capability and convergence speed. Finally, prior studies on carbon price prediction, driven by considerations of computational efficiency, have predominantly employed unidirectional sequence models, limiting their ability to fully capture the complex and dynamic behavior of carbon prices (Wang et al., 2024).

A review of existing research reveals that, despite notable progress in carbon price prediction, several challenges remain:

(1) Existing feature selection methods struggle to handle complex nonlinear relationships and computational efficiency.

(2) Prior studies commonly assume symmetric scaling factors for the upper and lower bounds and typically assign a fixed crossover probability in multi-objective optimization algorithms.

(3) Predictive models in earlier research have typically focused on capturing unidirectional sequences, which are insufficient to comprehensively characterize the complex dynamic behavior of carbon prices.

This study proposes a carbon price prediction framework that combines data processing, multi-objective optimization, and deep learning. The framework consists of three core modules: data processing and mining, optimization, and prediction, which work synergistically to enhance predictive accuracy and robustness.

- Data processing and mining module: The XGBoost feature selection method is applied to calculate feature importance scores associated with carbon prices. This process identifies the most influential features for accurate prediction.

- Optimization module: It constructs appropriate PIs through MSA. To improve the robustness and adaptability of interval prediction, an improved Non-dominated Sorting Genetic Algorithm II (NSGA-II) is incorporated to fine-tune the scaling parameters of the interval construction.
- Prediction module: A two-output BiLSTM model is utilized to generate interval prediction. By capturing both forward and backward temporal dependencies within the carbon price time series, BiLSTM effectively models the complex and dynamic nature of carbon markets. A two-output BiLSTM structure is adopted to simultaneously predict the lower and upper bounds of the price intervals.

The overall structure of the proposed framework is illustrated in Fig.4.1, demonstrating the sequential integration of feature selection, multi-objective optimization, and deep learning-based interval prediction. The main contributions of this study are summarized as follows:

(1) Improving carbon price predictive performance by selecting features with XGBoost to decrease computational complexity.

(2) The proposed MSA model constructs appropriate PIs, and an improved NSGA-II is utilized to optimize the hyperparameters of SA.

(3) The BiLSTM model is employed to capture both forward and backward temporal dependencies in the sequence, enhancing the modeling capability for the complex dynamic patterns of carbon prices.

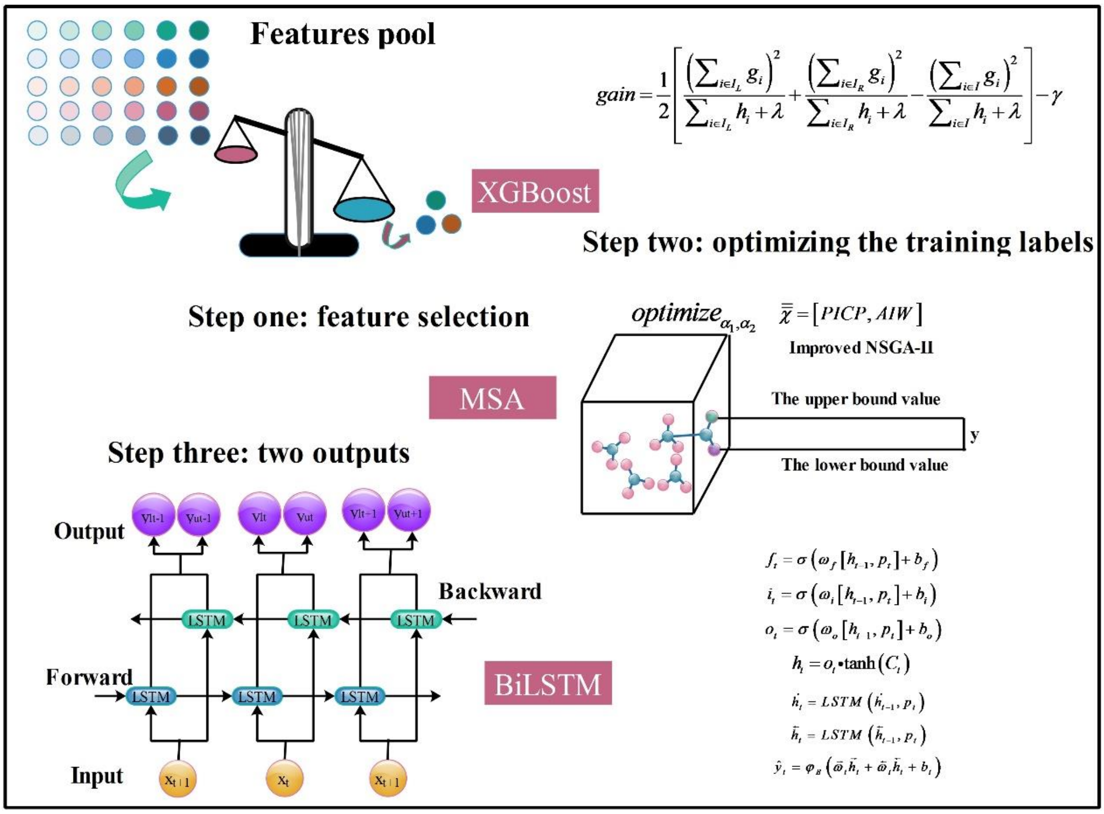


Fig. 4.1. The structure of the proposed framework.

This combination effectively overcomes the limitations identified in prior research. Specifically, XGBoost handles high-dimensional and nonlinear data while maintaining computational efficiency, thus addressing the limitations of traditional filter and wrapper methods. The improved NSGA-II introduces asymmetric scaling factors and an adaptive crossover probability, enhancing the flexibility and global search ability of interval construction. Meanwhile, the use of BiLSTM enables the model to learn from both past and future steps, compensating for the unidirectionality of earlier models.

4.2. Methodology

4.2.1. The feature selection of XGBoost

XGBoost, introduced by Chen and Guestrin (2016), built upon the gradient boosting decision tree framework. During the training process, the optimal split nodes are determined based on the gain metric. Feature importance scores are calculated based on the average gain, which reflects the relative contribution of each feature. The calculation of gain is given in Equation (1):

$$gain = \frac{1}{2}\left[\frac{\left(\sum_{i \in I_L} g_i\right)^2}{\sum_{i \in I_L} h_i + \lambda} + \frac{\left(\sum_{i \in I_R} g_i\right)^2}{\sum_{i \in I_R} h_i + \lambda} - \frac{\left(\sum_{i \in I} g_i\right)^2}{\sum_{i \in I} h_i + \lambda}\right] - \gamma \tag{4.1}$$

In Equation (1), the first and second order gradients are denoted by g_i and h_i, respectively. I, I_L and I_R represent the set of training samples in the parent, left child, and right child nodes, respectively. λ is the L2 regularization term on leaf weights. γ is the regularization term controlling the complexity. $i \in I$ is the summation index over samples in each respective node.

XGBoost can capture complex nonlinear relationships and optimize feature selection by evaluating feature importance. It improves computational efficiency and demonstrates strong generalization capability.

4.2.2. Modified scaling approach

SA avoids the need for prior assumptions about data distribution. This approach employs a dual-output model to directly generate interval prediction $\hat{y}_i = \left[\hat{y}_i^l, \hat{y}_i^u\right]$, $i = 1,...,m$ (Qin et al., 2015).

Interval-valued training labels $\bar{\bar{Y}} = \left[\left(y_1^l, y_1^h\right), \left(y_2^l, y_2^h\right), ..., \left(y_m^l, y_m^h\right)\right]$ are used to form the dataset $\left\{\left(x_1^{training}, y_1^l, y_1^h\right), \left(x_2^{training}, y_2^l, y_2^h\right), ..., \left(x_m^{training}, y_m^l, y_m^h\right)\right\}$ for model training. Here, y_m^l and y_m^h represent the lowest and highest single-day carbon price, respectively (Yan et al., 2024). However, since the closing price is a unidimensional value lacking explicit minimum and maximum values, interval-valued labels must be generated. To address this issue, scaling parameters are employed, following the methodology proposed by Shrivastava et al. (2016).

$$\bar{\bar{Y}} = \left[\bar{\bar{Y}}_{training} - \alpha \bar{\bar{Y}}_{training}, \bar{\bar{Y}}_{training} + \alpha \bar{\bar{Y}}_{training}\right] \tag{4.2}$$

Here, α is referred to as the scaling parameter. Previous studies have typically assumed equal values for both the scaling-down α and scaling-up α parameters, implying a symmetric distribution of the PIs. However, this assumption may not be optimal, especially considering the inherent variability and asymmetry often present in carbon price data. To address this limitation, the MSA does not enforce symmetry between these scaling parameters. Instead, α_1 and α_2 are treated as distinct parameters for scaling-down and scaling-up, respectively.

$$\bar{\bar{Y}} = \left[\bar{\bar{Y}}_{training} - \alpha_1 \bar{\bar{Y}}_{training}, \bar{\bar{Y}}_{training} + \alpha_2 \bar{\bar{Y}}_{training}\right] \tag{4.3}$$

In many studies, α is arbitrarily determined (Liu et al., 2021), disregarding dataset-specific characteristics. In the proposed MSA, the scaling-down parameter α_1 and the scaling-up parameter α_2 are adaptively determined, which directly optimize the quality of the PIs. This data-driven approach enhances both the practicality and efficiency of the interval prediction. The optimization problem can be formulated as follows:

Optimize

$$presub:\ \alpha_1,\alpha_2\ \ \bar{\bar{\chi}}=\sum_{n=1}^{N}\bar{\bar{\beta}}_n\bar{\bar{C}}_n$$

$$s.t.\begin{cases}\alpha_1^{\min}\le\alpha_1\le\alpha_1^{\max}\\ \alpha_2^{\min}\le\alpha_2\le\alpha_2^{\max}\\ \alpha_1>0\\ \alpha_2>0\end{cases} \tag{4.4}$$

Here, $\bar{\bar{C}}_n$ represents a criterion and $\bar{\bar{\beta}}_n$ is the weight assigned to the n-th criterion. However, determining the appropriate weight $\bar{\bar{\beta}}_n$ is a complex and non-trivial task. To address this issue, the optimization problem can be effectively handled through multi-objective optimization, which avoids the need for manually assigning weights. Hence, the optimization problem is reformulated and presented in Equation (4.5):

Optimize

$$presub:\ \alpha_1,\alpha_2\ \ \bar{\bar{\chi}}=\left[\bar{\bar{C}}_1,\bar{\bar{C}}_2,\ldots,\bar{\bar{C}}_n\right]$$

$$s.t.\begin{cases}\alpha_1^{\min}\le\alpha_1\le\alpha_1^{\max}\\ \alpha_2^{\min}\le\alpha_2\le\alpha_2^{\max}\\ \alpha_1>0\\ \alpha_2>0\end{cases} \tag{4.5}$$

This study employs prediction interval coverage probability (PICP) and average interval width (AIW) to assess the quality of the interval prediction. These two objectives are conflicting: the increasing PICP often results in a broader AIW, whereas a lower AIW may compromise coverage. Thus, balancing these objectives is crucial for optimal interval predictive performance. Therefore, Equation (4.5) can be reformulated as follows:

Optimize

$$presub:\ \alpha_1, \alpha_2\ \ \bar{\bar{\chi}} = [PICP, AIW]$$

$$s.t.\begin{cases} \alpha_1^{\min} \le \alpha_1 \le \alpha_1^{\max} \\ \alpha_2^{\min} \le \alpha_2 \le \alpha_2^{\max} \\ \alpha_1 > 0 \\ \alpha_2 > 0 \end{cases}$$

According to Wang et al. (2024), PICP and AIW are defined in Equation (4.6) and Equation (4.7), respectively:

$$PICP = \frac{1}{n}\sum_{i=1}^{n} b_i\,,\quad b_i = \begin{cases} 1, y_{target} \in \left[\hat{y}_i^l, \hat{y}_i^u\right] \\ 0, y_{target} \notin \left[\hat{y}_i^l, \hat{y}_i^u\right] \end{cases} \tag{4.6}$$

$$AIW = \frac{1}{n}\sum_{i=1}^{n}\left(\hat{y}_i^u - \hat{y}_i^l\right) \tag{4.7}$$

Here, b_i denotes a Boolean variable that indicates whether the interval for the observation includes the actual carbon price closing value. Specifically, if the carbon price falls within the predicted interval, it is denoted as 1; otherwise, it is denoted as 0.

In practice, a higher value for the PICP is typically desired, while a smaller value of the AIW is considered preferable. Moreover, PICP is expected to exceed the nominal confidence level μ (e.g., μ=0.9), as a low PICP value renders the AIW practically insignificant, no matter how narrow it is. Consequently, the issue transforms into a multi-objective optimization problem with constraints (MoOPC). Hence, Optimize is redefined as:

Optimize

$$presub:\ \alpha_1,\alpha_2\ \ \bar{\bar{\chi}}=[PICP,AIW]$$

$$s.t.\begin{cases}\alpha_1^{\min}\le\alpha_1\le\alpha_1^{\max}\\ \alpha_2^{\min}\le\alpha_2\le\alpha_2^{\max}\\ \alpha_1>0\\ \alpha_2>0\\ PICP\ge\mu\end{cases}$$

Metaheuristic algorithms are employed to solve the optimize due to their high flexibility and global optimization capabilities. In this study, this problem is addressed using an improved NSGA-II.

NSGA-II is recognized for its effectiveness in producing a well-distributed set of solutions and converging toward the Pareto-optimal front (Deb et al., 2002). Similar to other evolutionary algorithms, NSGA-II follows a sequence of key steps: initialization, selection, crossover and mutation.

In standard NSGA-II, the crossover probability is typically set at 50%. This fixed probability can hinder the algorithm's adaptability to the problem characteristics and the distribution of data at different stages of the optimization process. Consequently, it can adversely affect the algorithm's global search capability and convergence speed, resulting in an imbalance between diversity and convergence. In this study, the crossover process is improved by dynamically adjusting the crossover probability (Pc). Pc is dynamically adjusted based on the current generation (gen) and the maximum generation ($\max\_gen$) of the genetic algorithm to balance the exploration and convergence processes of the algorithm. This adjustment allows the algorithm to explore more broadly during the early stages and to focus more on convergence during the later stages. The calculation of Pc is as follows:

$$Pc = Pc_{\min} + \left(Pc_{\max} - Pc_{\min}\right)\left(1 - \frac{gen}{\max\_gen}\right) \tag{4.8}$$

Here $Pc_{\min}$ and $Pc_{\max}$ denote the minimum and maximum values of the crossover probability, respectively. As the generations increase, Pc gradually decreases from $Pc_{\max}$ to $Pc_{\min}$.

To ensure that a smaller AIW value is obtained when PICP reaches or exceeds 0.9, the following mechanisms are proposed:

- Filtering mechanism: When the PICP of a feasible solution meets or exceeds the threshold μ, the algorithm selects the feasible solution with the smallest AIW value among all such solutions as the optimal solution.
- Amnesia mechanism: If the PICP of a feasible solution falls below the threshold μ, the improved NSGA-II triggers an amnesia process, in which the previously identified best solution is disregarded and the algorithm recomputes the search space.

4.2.3. Two-output bidirectional long short-term memory

Long Short-Term Memory (LSTM) is a deep learning model introduced by Hochreiter and Schmidhuber (1997). By integrating both forward and backward LSTM models, a bidirectional LSTM is formed, which enables the learning of bidirectional long-term dependencies and provides enhanced contextual understanding of the data (Graves and Schmidhuber, 2005; Nguyen et al., 2021).

The forward LSTM computes output by processing inputs sequentially from Step 1 to Step 3, while the backward LSTM processes inputs in reverse order. For the input p_t at time t, $\vec{h}_t$ and $\bar{h}_t$ represent the hidden layer outputs. A detailed explanation of the LSTM is provided below.

Step 1: The forget gate computes the factor f_t to determine the retention of crucial information from the previous cell state C_{t-1}:

$$f_t = \sigma\left(\omega_f\left[h_{t-1}, p_t\right] + b_f\right) \tag{4.9}$$

Here, h_{t-1} denotes the hidden layer output at time $t-1$. ω_f and b_f represent the weight matrix and bias of the forget gate, respectively. σ denotes a sigmoid function that produces a value within the range of 0 to 1.

Step 2: The input gate updates the cell state by determining which new information should be added to the current cell state. The update is expressed as follows:

$$\hat{C}_t = \tanh\left(\omega_c\left[h_{t-1}, p_t\right] + b_c\right) \tag{4.10}$$

$$i_t = \sigma\left(\omega_i\left[h_{t-1}, p_t\right] + b_i\right) \tag{4.11}$$

$$C_t = f_t C_{t-1} + i_t \hat{C}_t \tag{4.12}$$

In Equations (12)-(14), $\hat{C}_t$ represents the current cell state, which contains the information of p_t and h_{t-1}. $\tanh(\bullet)$ represents the activation function that generates $\hat{C}_t$ ranging from −1 to 1. ω_c, ω_i and b_c, b_i are the weight matrices and bias terms, respectively.

Step 3: The output gate computes o_t to determine the amount of information from C_t that should be output and passed to h_t. The output h_t is obtained as follows:

$$o_t = \sigma\left(\omega_o\left[h_{t-1}, p_t\right] + b_o\right) \tag{4.13}$$

$$h_t = o_t \odot \tanh\left(C_t\right) \tag{4.14}$$

The computational procedure of the BiLSTM is given below:

$$\vec{h}_t = LSTM\left(\vec{h}_{t-1}, p_t\right) \tag{4.15}$$

$$\overleftarrow{h}_t = LSTM\left(\overleftarrow{h}_{t-1}, p_t\right) \tag{4.16}$$

$$\hat{y}_t = \varphi_B\left(\vec{\omega}_t \vec{h}_t + \overleftarrow{\omega}_t \overleftarrow{h}_t + b_t\right) \tag{4.17}$$

In Equations (4.15)-(4.17), $\vec{\omega}_t$, $\overleftarrow{\omega}_t$ and b_t are the weight matrix of the forward layers, weight matrix of the backward layers and the output layer bias, respectively. The activation function $\varphi_B(\bullet)$ merges $\vec{h}$ and $\overleftarrow{h}_t$ into $\hat{y}_t$.

4.3. Experimental analysis and discussion

To validate the advantages of the proposed framework, this section presents carbon price interval forecasting using datasets from the Hubei and Guangdong carbon markets. Three comparative experiments are conducted to assess its performance.

4.3.1. The dataset

The Hubei and Guangdong carbon market feature a well-developed and active trading market. For the empirical analysis, this study utilizes daily closing prices from both markets, sourced from the Wind dataset. The Hubei dataset comprises 1,155 daily samples spanning from January 2, 2018, to July 31, 2023. The Guangdong dataset consists of 738 daily samples covering the period from September 24, 2020, to April 3, 2024. Each dataset is divided into training and test sets at a ratio of 4:1. Specifically, the training sets cover the periods from January 2, 2018, to May 9, 2022 (Hubei), and from September 24, 2020, to July 27, 2023 (Guangdong). The corresponding test sets extend from June 15, 2022, to July 31, 2023 (Hubei), and from July 28, 2023, to April 3, 2024 (Guangdong). A summary of the basic characteristics of these datasets is provided in Table 1, with additional details illustrated in Fig. 4.2.

In addition to carbon market prices, this study considers various influencing factors, including stocks, energy, market sentiment, exchange rates and interest rates:

- Stock-related factors: these factors are primarily derived from stock market indices, such as the Shanghai Stock Exchange Index and the Dow Jones Industrial Average. As key indicators of overall economic performance, these indices enable to assess economic conditions.
- Energy-related factors: global energy market dynamics are captured by factors such as ICE Rotterdam Coal and Brent

Crude oil prices, which typically reflect the supply and demand conditions in the energy sector.

- Market sentiment-related factors: assets like London Gold, SHFE Gold, COMEX Gold and the Chicago Board Options Exchange provide insights into investor confidence and risk appetite, which offers valuable information to assess financial market sentiment that may influence carbon price volatility.
- Exchange rate-related factors: these factors, including EUR/CNY, EUR/USD, USD/CNY and the USD index, influence carbon prices by affecting international trade costs, investment flows and broader economic activity.
- Interest rate-related factors: SHIBOR and U.S. Treasury Securities (3M and 10Y) provide insights into macroeconomic conditions, monetary policy and investment risk preferences.

All data were taken from the Wind database (https://www.wind.com.cn/), and detailed information is presented in Table 4.2.

Table 4.1.

Details of datasets from Hubei and Guangdong.

Dataset	Samples	Sample size	Max	Min	Mean	Std.
Hubei	All samples	1155	61.48	14.07	33.49	10.33
	Training	924	61.48	14.07	29.95	8.37
	Testing	231	51.33	43.1	47.66	1.44
Guangdong	All samples	741	95.26	27.11	61.22	19.80
	Training	593	95.26	27.11	59.75	21.80
	Testing	148	77.04	60.57	67.08	3.75

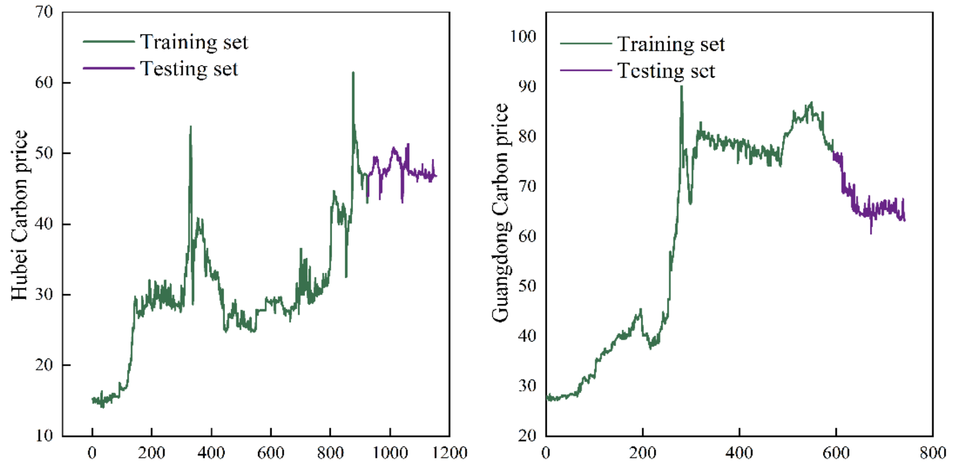


Fig. 4.2. Detailed characteristics of datasets.

Table 4.2.

Influencing factors of carbon price.

Classification	External affected factors	Symbol	Classification	External affected factors	Symbol
Stock factors	Shanghai Stock Exchange Index	000001.SH		NYMEX N.Gas	NG.NYM
	Shanghai Stock Exchange Composite Index	000008.SH	**Market Sentiment factors**	London Gold	SPTAUUSDOZ.IDC
	Shenzhen Component Index	399001.SZ		SHFE Gold	AU.SHF
	Dow Jones Industrial Average	DJI.GI		Chicago Board Options Exchange	VIX.GI
	Nasdaq Composite Index	IXIC.GI	**Exchange rate factors**	EUR/CNY	EURCNY.IB
	Deutscher Aktien Index	GDAXI.GI		EUR/USD	EURUSD.FX
	FTSE Global Equilty Index	FTSE 100		USD/CNY	USDCNY.IB
	Cotation Assistée en Continu 40	FCHI.GI		USD	USDX.FX
	S&P 500 Index	SPX.GI	**Interest rate factors**	SHIBOR	SHIBORON.IR
Energy factors	ICE Rotterdam Coal	ATW.IPE		U.S. Treasury Securities 3M	3MOBILL.GBM

COKING COAL2401	J2401.DCE	U.S. Treasury Securities 10Y	10YRNOTE.GBM
Brent Crude	B.IPE		
NYMEX WTI	CL.NYM		

4.3.2. Hyper-parameter settings

In this study, the key hyper-parameters for the XGBoost model were set as follows: gamma = 0, learning_rate = 0.1, max_depth = 7 and n_estimators = 100. For enhanced clarity, Table 4.3 presents the primary hyper-parameter configurations. This table encompasses not only the proposed model but also comparative models such as NSGA-II, multi-objective evolutionary algorithm/decomposition (MOEA/D), indicator-based evolutionary algorithm (IBEA), gated recurrent unit (GRU), BiLSTM, LSTM and temporal convolutional network (TCN).

Table 4.3.

The hyper-parameters of the models.

Algorithm	Hyper-parameter	Value
Proposed model	pop_size	30
	max_gen	5
	min_value	0.2 for Hubei; 0.3 for Guangdong
	max_value	0.3 for Hubei; 0.4 for Guangdong
NSGA-II	pop_size	30
	max_gen	5
	crossover probability	0.9
	min_value	0.2 for Hubei; 0.3 for Guangdong
	max_value	0.3 for Hubei; 0.4 for Guangdong
MOEA/D	pop_size	30
	max_gen	5
	neighborhood size	15
	min_value	0.2 for Hubei; 0.3 for Guangdong
	max_value	0.3 for Hubei; 0.4 for Guangdong
IBEA	pop_size	30

	max_gen	5
	epsilon	0.05
	min_value	0.2 for Hubei; 0.3 for Guangdong
	max_value	0.3 for Hubei; 0.4 for Guangdong
GRU	hidden layer nodes	64
	dropout	0.3
	epochs	50
	learning rate	0.002
	timestep	1
	dateback	6
BiLSTM	hidden layer nodes	64
	dropout	0.3
	epochs	50
	learning rate	0.002
	timestep	1
	dateback	6
LSTM	hidden layer nodes	64
	dropout	0.3
	epochs	50
	learning rate	0.002
	timestep	1
	dateback	6
TCN	hidden layer nodes	64
	dropout	0.3
	epochs	50
	learning rate	0.002
	timestep	1
	dateback	6

4.3.3. Evaluation metrics

CWC is employed for a more comprehensive evaluation, as it integrates both interval coverage and width:

$$CWC = AIW \times \left(1 + \gamma e^{-\eta(PICP-\mu)}\right)$$

$$\gamma = \begin{cases} 0, PICP \geq \mu \\ 1, PICP < \mu \end{cases} \tag{4.20}$$

Here, the parameter η is set as 15, as recommended by Wang et al. (2023). Achieving reliable forecasts with sufficient coverage probability is crucial for decision-makers (Shrivastava et al., 2016). Therefore, in the performance comparisons, the PICP values are required to exceed 0.9, as denoted by μ ($\mu \geq 0.9$). Once the PICP values are confirmed to be satisfactory, the AIW values are then compared to assess the performance of the models.

4.3.4. Model comparison

4.3.4.1. Comparison with feature selection methods

The relevance of each feature is quantitatively evaluated using the XGBoost method. Additionally, comparative feature selection methods, such as MI, ridge regression (RR) and RFE are employed to verify the effectiveness of different selection models.

Tables 4.4 and 4.5 demonstrate the superior performance of the XGBoost feature selection method compared to MI, RR and RFE, particularly in terms of the key metrics PICP, AIW and CWC. For the Hubei dataset, all models achieved PICP values above 0.9, with the proposed model reaching a value of 0.92. Since PICP values exceeded the 0.9 threshold, the AIW and CWC values became the primary metrics for comparison. The AIW achieved by the proposed model was only 2.33, considerably lower than the AIW values of the MI, RR and RFE models, which were 2.52, 2.44 and 2.42, respectively. Consequently, the proposed model achieved a marked improvement in CWC, with reductions of 7.54%, 4.51% and 3.72% compared to MI, RR and RFE, respectively.

For the Guangdong dataset, the PICP values for all models exceeded 0.9 again, with the proposed model achieving the highest value of 0.94. In terms of CWC, the proposed model demonstrated a value of 5.01, outperforming MI (5.02), RR (5.08) and RFE (5.19). The improvements in CWC are 0.2%, 1.38% and 3.47%, respectively, compared to the benchmark methods.

These findings highlight the capability of the XGBoost feature selection in improving predictive accuracy and enhancing the quality of PIs. Its ability to evaluate feature importance through gain-based assessments, capture complex nonlinear relationships, and eliminate redundant or irrelevant features makes XGBoost a superior approach to feature selection.

By analyzing the features identified by various feature selection methods, as detailed in Tables 4 and 5, several key input features were highlighted for the Hubei and Guangdong datasets. For the Hubei dataset, the most influential features were ICE Rotterdam Coal, SHFE Gold and U.S. Treasury Securities 3M, reflecting the importance of energy and market sentiment factors in this region. For the Guangdong dataset, EUR/USD and U.S. Treasury Securities 10Y emerged as important, indicating a stronger influence from exchange and interest rate factors. To visually illustrate the importance of these features, Fig. 2 presents the results of the XGBoost feature selection method. The analysis shows that in the Hubei market, carbon price fluctuations are primarily driven by energy, market sentiment and interest rate-related factors. In the Guangdong market, interest rates, exchange rates and stock-related factors play a more dominant role. These findings highlight the varying drivers of carbon price dynamics in different regions, which emphasizes the importance of tailoring predictive models to specific market conditions.

Table 4.4.

Results of models with different feature selections for Hubei.

Models	Feature	PICP	AIW	CWC
MI-improved NSGA-II-BiLSTM	S&P 500 Index ICE Rotterdam Coal U.S. Treasury Securities 3M	0.92	2.52	2.52
RR-improved NSGA-II-BiLSTM	U.S. Treasury Securities 3M U.S. Treasury Securities 10Y	0.92	2.44	2.44
RFE-improved NSGA-II-BiLSTM	EURUSD USDCNY SHIBOR	0.92	2.42	2.42
Proposed model	ICE Rotterdam Coal SHFE Gold U.S. Treasury Securities 3M	0.92	2.33	2.33

Table 4.5.

Results of models with different feature selections for Guangdong.

Models	Feature	PICP	AIW	CWC
MI-improved NSGA-II-BiLSTM	Shenzhen Component Index U.S. Treasury Securities 3M	0.92	5.02	5.02
RR-improved NSGA-II-BiLSTM	EURCNY U.S. Treasury Securities 3M	0.90	5.08	5.08
RFE-improved NSGA-II-BiLSTM	EURUSD USDCNY	0.93	5.19	5.19
Proposed model	EURUSD U.S. Treasury Securities 10Y	0.94	5.01	5.01

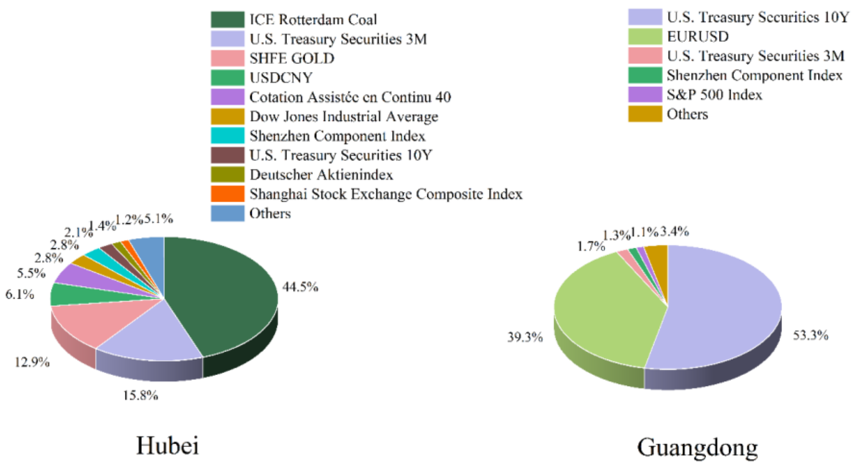


Fig. 4.2. Feature importance of datasets.

4.3.4.2. Comparison with interval prediction methods

As described in Section 3.4.1, the XGBoost-based feature selection method demonstrates significant advantages in feature selection. Accordingly, we adopt this method for the subsequent comparative analysis between the proposed model and other interval prediction methods. To ensure a fair comparison, we construct hybrid models that integrate XGBoost with the Error distribution, KDE, and QR method, respectively. The specific model construction approaches are detailed in Table 4.6. Tables 4.7 and 4.8, as well as Figs 4.3 and 4.4, present the prediction results using different interval prediction methods on the Hubei and Guangdong datasets, respectively.

For the Hubei dataset, the Error distribution model achieves the highest PICP; however, this comes at the cost of wider PIs, resulting in significantly higher AIW and CWC values compared to other models. The XGBoost-BiLSTM-KDE model outperforms the Error distribution in terms of AIW and CWC. This indicates that, compared to the strong assumptions required by the Error distribution method regarding the error distribution, KDE provides a more flexible and realistic fit to the actual distribution. Furthermore, the XGBoost-QR-BiLSTM model outperforms the XGBoost-BiLSTM-KDE model, potentially due to the limitations of KDE, which employs fixed interval boundaries across all samples and thus struggles to capture local and temporal variability. In contrast, XGBoost-QR-BiLSTM directly learns the quantiles of the conditional distribution of the target variable, enabling dynamic adjustment of interval boundaries. The proposed model and the XGBoost-QR-BiLSTM exhibit the same PICP, but the proposed model achieves superior AIW and CWC values. This is attributed to the use of a multi-objective optimization algorithm, which ensures that the PICP exceeds 90% while simultaneously obtaining the narrowest possible interval width.

For the Guangdong dataset, the proposed model and the XGBoost-QR-BiLSTM significantly outperform the Error distribution and the XGBoost-BiLSTM-KDE. This is because the latter two methods add a fixed interval after point prediction instead of directly estimating the interval boundaries, resulting in lower prediction accuracy.

Table 4.6.

Comparison of models' descriptions

Hybrid model	Explanation
XGBoost-BiLSTM-Error distribution	Based on the error distribution method, assuming that the errors follow a normal distribution.
XGBoost-BiLSTM-KDE	Based on the KDE method, with bandwidth determined using the gray grid method.
XGBoost-QR-BiLSTM	Based on the quantile method, the lower and upper bounds of the interval correspond to the 5th and 95th percentiles, respectively.

Table 4.7.

Results of models with different interval prediction methods for Hubei.

Models	Serial number	PICP	AIW	CWC
XGBoost-BiLSTM-Error distribution	Model 1	0.95	6.74	6.74
XGBoost-BiLSTM-KDE	Model 2	0.91	5.29	5.29
XGBoost-QR-BiLSTM	Model 3	0.92	3.16	3.16
The proposed model	Model 4	0.92	2.33	2.33

Table 4.8.

Results of models with different interval prediction methods for Guangdong.

Models	Serial number	PICP	AIW	CWC
XGBoost-BiLSTM-Error distribution	Model 1	0.87	3.84	9.86
XGBoost-BiLSTM-KDE	Model 2	0.88	3.87	9.10
XGBoost-QR-BiLSTM	Model 3	0.94	5.16	5.16
The proposed model	Model 4	0.94	5.01	5.01

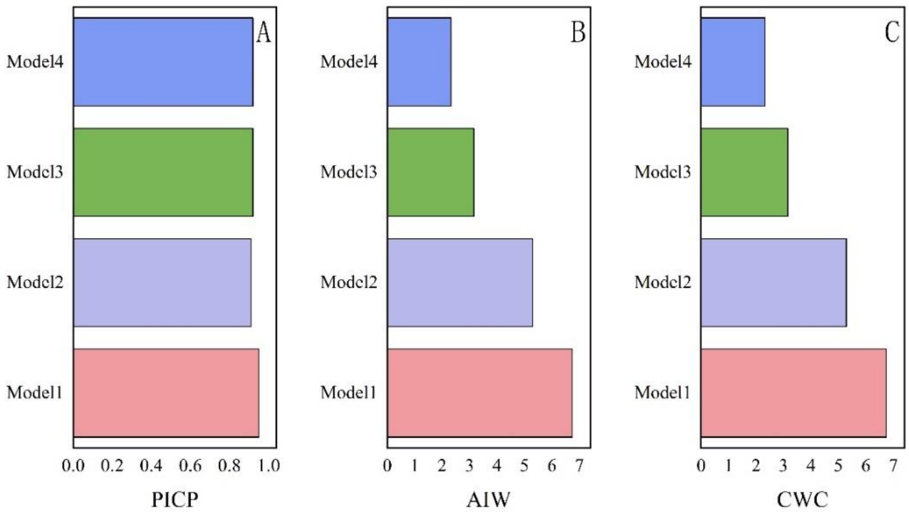


Fig. 4.3. Results of models with different interval prediction methods for Hubei.

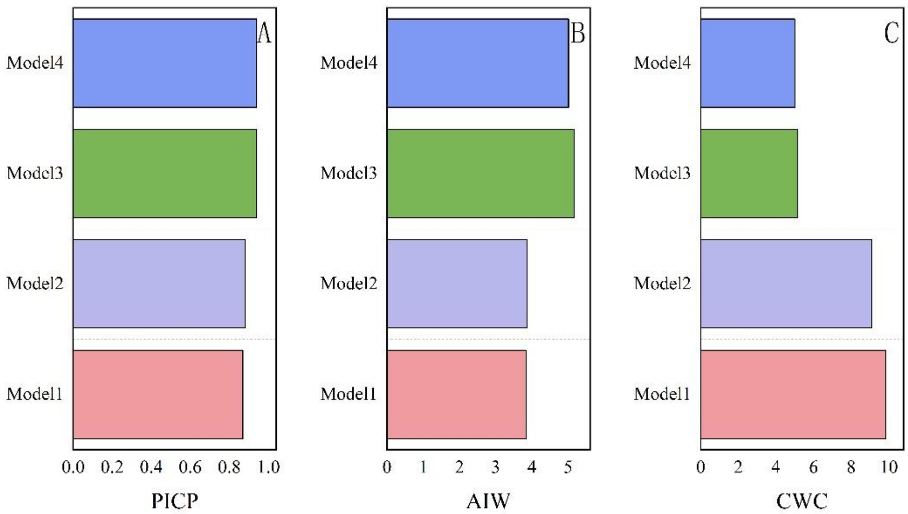


Fig. 4.4. Results of models with different interval prediction methods for Guangdong.

4.3.4.3. Comparison with optimization algorithms

The PIs generated by the proposed model, which employs the improved NSGA-II, are compared against those from standard optimization algorithms (NSGA-II, MOEA/D, IBEA) and a conventional scaling approach with fixed scaling parameters. For the fixed-parameter models, scaling parameters are set to 0.2 and 0.3 for the Hubei dataset, and 0.3 and 0.4 for the Guangdong dataset. Performance results are summarized in Tables 4.8-4.9 and Figs 4.5-4.6.

Tables 4.8 and 4.9 show that most models achieve PICP values exceeding 0.9, except for MOEA/D (Hubei) and fixed scaling parameters of 0.2 (Hubei) and 0.3 (Guangdong). The proposed model demonstrates the highest PICP values: 0.92 for the Hubei dataset and 0.94 for the Guangdong dataset. In contrast, the fixed-parameter models achieve lower PICP values (e.g., 0.92 for Hubei with a 0.3 scaling parameter and 0.91 for Guangdong with a 0.4 scaling parameter). Furthermore, the AIW values for the fixed-parameter models are considerably higher, which indicates their inability to maintain both narrow intervals and high coverage accuracy.

For the Hubei dataset, the proposed model outperforms all comparative models in both PICP and CWC. The PICP of the proposed model is 0.92, compared to 0.91 for NSGA-II, 0.89 for MOEA/D, and 0.91 for IBEA. The CWC value of the proposed model is 2.33, so there are improvements of 6.12%, 51.15% and 1.69% over NSGA-II (2.45), MOEA/D (4.77) and IBEA (2.37), respectively. For the Guangdong dataset, the proposed model achieves the highest PICP of 0.94, surpassing the other models. Its CWC value is also the lowest, with relative improvements of 3.65% over NSGA-II and 1.38% over MOEA/D.

The superior performance of the proposed model is attributed to the improved NSGA-II algorithm. By dynamically adjusting the crossover probability, the algorithm maintains population diversity, enabling a broader exploration of the solution space. This prevents premature convergence to local optima and enhances the efficiency of parameter optimization.

Table 4.8.

Results of models with different multi-objective optimization algorithms for Hubei.

Models	Serial number	PICP	AIW	CWC
XGBoost-NSGA-II-BiLSTM	Model 1	0.91	2.45	2.45
XGBoost-MOEA/D-BiLSTM	Model 2	0.89	2.21	4.77
XGBoost-IBEA-BiLSTM	Model 3	0.91	2.37	2.37
Scaling parameter of 0.2	Model 4	0.85	1.80	5.62
Scaling parameter of 0.3	Model 5	0.92	2.74	2.74
Proposed model	Model 6	0.92	2.33	2.33

Table 4.9.

Results of models with different multi-objective optimization algorithms for Guangdong.

Models	Serial number	PICP	AIW	CWC
XGBoost-NSGA-II-BiLSTM	Model 1	0.92	5.20	5.20
XGBoost-MOEA/D-BiLSTM	Model 2	0.92	5.08	5.08
XGBoost-IBEA-BiLSTM	Model 3	0.91	5.00	5.00
Scaling parameter of 0.3	Model 4	0.80	4.39	24.06
Scaling parameter of 0.4	Model 5	0.91	5.55	5.55
Proposed model	Model 6	0.94	5.01	5.01

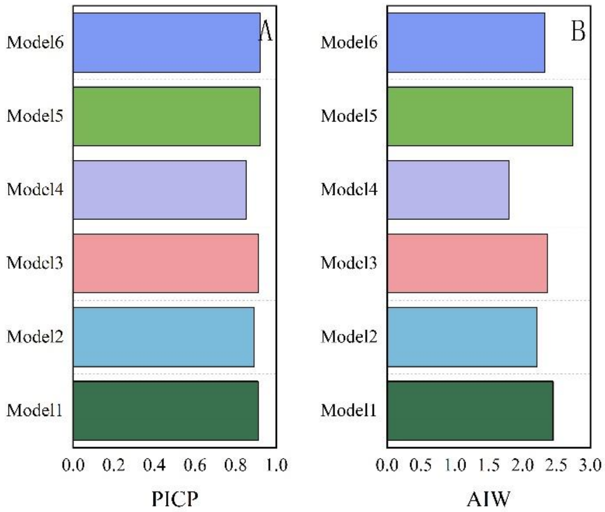


Fig. 4.5. Results of models with different multi-objective optimization algorithms for Hubei.

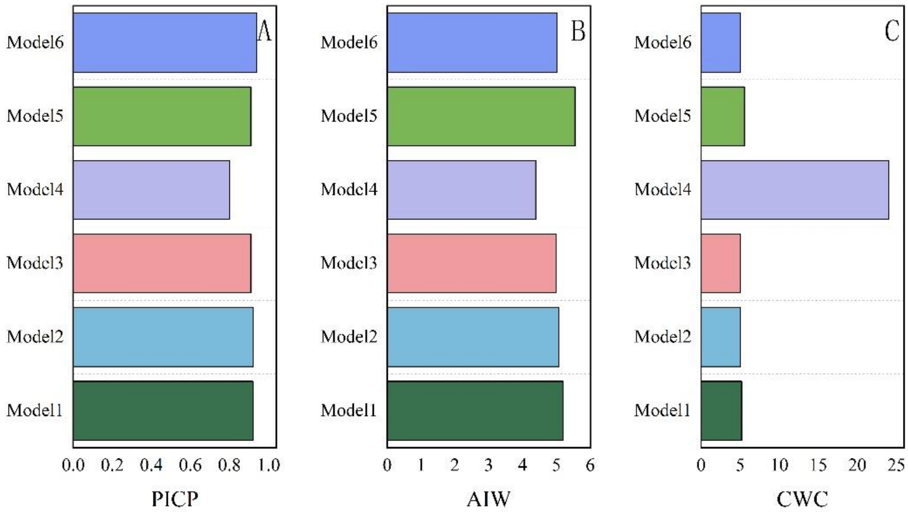


Fig. 4.6. Results of models with different multi-objective optimization algorithms for Guangdong.

4.3.4.4. Comparison with prediction models

This subsection further compares the BiLSTM predictive model with other baseline models, including GRU, LSTM, and TCN.

Tables 4.10-4.11 and Figs 4.7-4.8 compare the BiLSTM model with baseline models, including GRU, LSTM and TCN, for the Hubei dataset. While the GRU, LSTM and BiLSTM models all achieve the same PICP value of 0.92, the proposed BiLSTM model demonstrates a clear advantage in terms of interval quality. It achieves a CWC value of 2.33, outperforming GRU, LSTM and TCN by 10.73%, 3.72% and 16.19%, respectively. This highlights the BiLSTM model's ability to produce narrower PIs while maintaining high coverage accuracy. For the Guangdong dataset, the BiLSTM model outperforms all baseline models in both PICP and CWC. It achieves a PICP value of 0.94, considerably higher than those of the GRU, LSTM and TCN models. Furthermore, the BiLSTM model reduces the CWC value by 7.90%, 1.18%, and 1.96%, respectively, compared to the GRU, LSTM and TCN models. These results emphasize the robustness of the BiLSTM model in handling data variability in different regions.

The results highlight the BiLSTM model's superior performance in interval prediction. It captures both forward and backward dependencies in time series through bidirectional information flow, thereby enhancing prediction accuracy while generating narrower PIs with high coverage. This combination of strengths establishes the proposed model as a reliable and robust choice for carbon price prediction.

Table 4.10.

Results of different prediction models for Hubei.

Models	Serial number	PICP	AIW	CWC
XGBoost-Improved NSGA-II-GRU	Model 1	0.92	2.61	2.61
XGBoost-Improved NSGA-II-LSTM	Model 2	0.92	2.42	2.42
XGBoost-Improved NSGA-II-TCN	Model 3	0.91	2.78	2.78
The Proposed	Model 4	0.92	2.33	2.33

Table 4.11.

Results of different prediction models for Guangdong.

Models	Serial number	PICP	AIW	CWC
XGBoost-Improved NSGA-II-GRU	Model 1	0.93	5.44	5.44
XGBoost-Improved NSGA-II-LSTM	Model 2	0.90	5.07	5.07
XGBoost-Improved NSGA-II-TCN	Model 3	0.91	5.11	5.11
The Proposed	Model 4	0.94	5.01	5.01

The comparison highlights the contributions of each module in the proposed system. The XGBoost identifies essential features with high predictive importance while eliminating redundant ones. The MSA adaptively selects scaling parameters to optimize interval quality. The improved NSGA-II achieves parameter optimization by effectively managing population diversity and preventing premature convergence to local optima. Finally, the BiLSTM model strengthens the ability to learn complex nonlinear patterns. Collectively, these techniques enable the proposed model to generate accurate and efficient interval prediction.

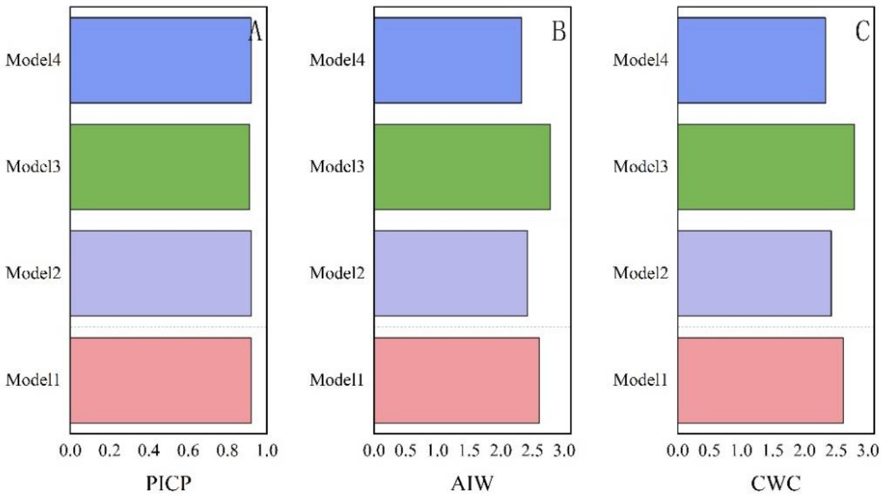


Fig. 4.7. Results of models with prediction models for Hubei.

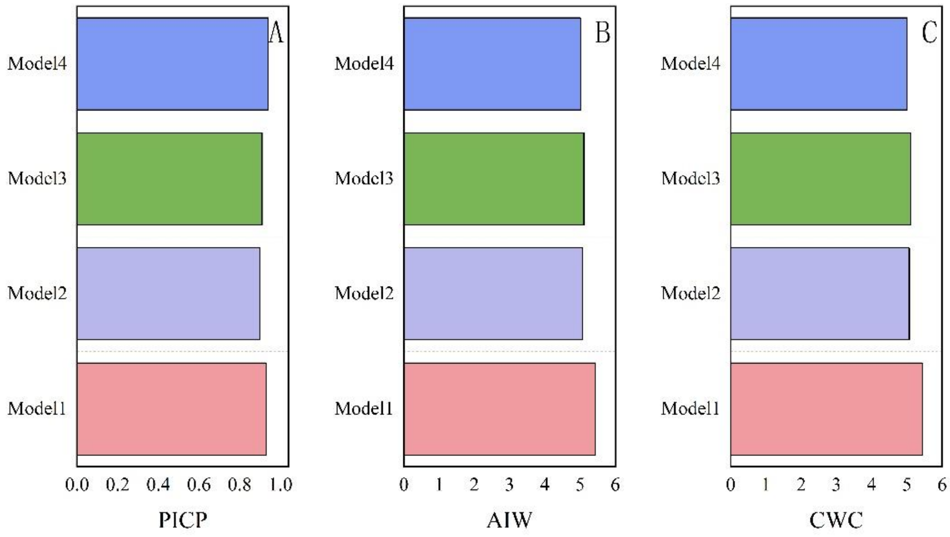


Fig. 4.8. Results of models with prediction models for Guangdong.

4.4. Summary

In this study, an interval prediction framework to address the challenges of carbon price interval prediction has been introduced. This paper contributes to the following aspects:

(1) The XGBoost feature selection method identifies key predictive features while removing redundancies, resulting in an appropriate feature set.

(2) The proposed MSA interval prediction approach directly outputs PIs and adaptively determines optimal scaling parameters using the improved NSGA-II algorithm, thereby generating accurate and reliable interval prediction.

(3) The BiLSTM model improves its capacity to capture complex nonlinear patterns in carbon pricing data by leveraging both forward and backward dependencies.

These advanced techniques collectively enable the presented model to overcome the limitations of existing interval prediction methods and generate accurate and efficient PIs. Experimental results demonstrate that the proposed framework enhances the CWC metric by 11.71% and 2.35% for the two datasets, respectively, underscoring its reliability and effectiveness. This study therefore offers a practical tool for market participants and policymakers to make informed decisions, manage uncertainties and ensure the stable operation of carbon trading markets.

5. Subsidy-driven production strategies in a duopoly apparel market: Comparative analysis under policy intervention

5.1. Introduction

From the corporate perspective, sustainable technological innovation not only helps optimize resource efficiency and improve environmental quality but also enables firms to gain a differentiated competitive advantage by cultivating a sustainable brand image (Leal et al., 2019; AlMulhim, 2021; Yang et al., 2022). However, it is noteworthy that such innovations are often associated with high R&D costs (Lotha et al., 2024; Shaw et al., 2024), which can diminish firms' willingness to undergo transformation in the absence of external incentives (Kazancoglu et al., 2021). Therefore, exploring effective incentive mechanisms to achieve synergy between economic growth and environmental protection has become a key issue in promoting the sustainable transformation of the apparel industry, with significant practical implications (Akter et al., 2022; Shamsuzzaman et al., 2023). In response to this issue, academic research has primarily focused on the following two areas:

First, the role of government regulation in promoting sustainable technological advancement in apparel firms. Existing studies highlight that sustainable technological innovation exhibits dual characteristics of positive environmental externalities and technological spillovers, thereby justifying government intervention as a necessary response to market failure (Duan et al., 2024; Lin and Zhang, 2024; Feng et al., 2024). For instance, the government can impose environmental taxes to modify the cost structures of apparel firms, thereby incentivizing sustainable technological innovation (Liu and Li, 2024). However, firms may pass the increased costs associated with environmental taxes onto consumers, thereby undermining the effectiveness of such policies (Lin and Li, 2011). Moreover, the implementation of environmental taxes relies on stringent monitoring of corporate emissions, which in turn raises government regulatory costs (Stavins, 2003; Gu et al., 2021). By contrast, government subsidies to firms, as a form of positive incentive, can directly reduce the costs associated with using eco-friendly materials and clean technologies, thereby promoting the supply of sustainable products, stabilizing market prices, and protecting consumer welfare (Meng et al., 2021; Lin et al., 2024; Liu et al., 2024). Furthermore, subsidies help mitigate firms' incentives to conceal emission data, thereby reducing the information acquisition and verification costs for the government (Chen et al., 2023). Nevertheless, subsidizing producers entails potential risks: excessive subsidies may encourage fraudulent behavior or institutional rent-seeking by firms, thereby weakening policy implementation and leading to the misallocation of public resources (Dimos and Pugh, 2016). On the other hand, insufficient subsidies may fail to offset the high initial investment and transformation costs of adopting sustainable technologies, thereby discouraging adoption and diminishing policy effectiveness (Yu et al., 2023; Zhou et al., 2025). To broaden the scope of incentives, some scholars have begun focusing on consumer-oriented subsidy strategies (Hur and Faragher-Siddall, 2022). Studies show that although consumers recognize the environmental value of sustainability, the relatively high price of sustainable apparel limits its market acceptance to some extent (Kamboj and Matharu, 2021; Valencia-Arias et al., 2025). To address this issue, the government can provide subsidies to consumers to lower the actual cost of purchasing sustainable apparel, thereby enhancing their willingness and behavior to buy (Guo et al., 2024). However, this mechanism is not without flaws; for instance, consumer subsidies may drive up overall prices, indirectly harming the welfare of non-subsidized consumers. In summary, to maximize the incentive effect of government subsidies in promoting green transformation in the apparel industry, subsidy mechanisms should holistically address the heterogeneous needs of both firms and consumers. This requires integrating factors such as firms' technological capabilities, market structure, consumer income levels, and environmental preferences to enhance the precision and effectiveness of policy implementation (Ding et al., 2022; Liu et al., 2022).

Second, the role of market mechanisms in driving sustainable technological progress. These studies primarily investigate how market forces can effectively incentivize firms to engage in sustainable technological innovation (Mazaheri et al., 2022; Syväri et al., 2025). In the field of supply chain management, numerous studies have examined the collaborative efforts of suppliers, manufacturers, and retailers in advancing the development and application of sustainable technologies (Chen et al., 2017; Kunkel et al., 2022; Chauhan et al., 2022). In recent years, growing consumer concern for environmental issues has led scholars to recognize the critical role of environmental awareness in sustainable supply chain management, incorporating it as a key variable into analytical frameworks (Gong et al., 2019; Li and Xiong, 2025). Studies have shown that consumer environmental awareness can effectively stimulate demand for sustainable apparel, expand its market share, and enhance firm profitability, thereby motivating increased investment in sustainable technology R&D (Xing and Lee, 2024; Khan et al., 2022; Vasileiou et al., 2022). In fact, consumer environmental awareness largely determines the market acceptance of sustainable products and serves as a key driving force in advancing the sustainable transformation of the apparel industry (Jimenez et al., 2023; Hong et al., 2024). Notably, in contexts where consumer environmental awareness is weak, even well-designed sustainable policies may fail to generate lasting effects in the market (Schoenmacker et al., 2022).

Despite notable progress in existing research, several key gaps remain:

(1) While prior studies have acknowledged the critical roles of government subsidies and consumer environmental awareness in driving sustainable technological innovation, most analyses adopt a single-dimensional perspective and lack a systematic investigation of their synergistic effects.

(2) Although many studies recognize that both producer and consumer subsidies influence stakeholders' behavioral strategies, few

have conducted in-depth comparative analyses of the differences between these two subsidy approaches.

(3) Current research primarily focuses on sustainable apparel supply chains, with limited attention to the competitive interactions between traditional and sustainable apparel firms in the same market. As a result, systematic analysis of key factors such as product pricing, market structure, firm profitability, and social welfare remains insufficient.

Building upon previous research, this study addresses the following aspects:

(1) Analyze the synergistic effects of government subsidies and consumer environmental awareness, and explore how their interaction jointly motivates apparel firms to increase investment in sustainable technology R&D.

(2) Develop separate models for producer and consumer subsidies to compare their effects on the behavioral strategies of relevant stakeholders.

(3) Construct a duopoly competition model involving traditional and sustainable apparel firms to systematically examine how government subsidies and consumer environmental awareness influence product pricing, market structure, firm profitability, and social welfare.

5.2. Model Development and Assumptions

5.2.1. Model description

There are two clothing companies in the market, each with the capability to produce either traditional or sustainable apparel. Consumers choose between the two types based on the utility derived from each option, denoted by u_1 and u_2, respectively. The utility functions are defined as follows:

$$\begin{cases} u_1 = u_0 - p_1 \\ u_2 = u_0 + \alpha \Delta u - p_2 \end{cases} \tag{5.1}$$

Here, u_0 denotes the basic utility derived from fulfilling the fundamental need for apparel. Δu represents the additional utility gained from sustainable apparel. p_1 and p_2 are the prices of traditional apparel and sustainable apparel, respectively. The parameter α represents the consumer's sensitivity to the additional utility provided by sustainable apparel. It is assumed to follow a uniform distribution over the interval (0,1), with the corresponding probability density function:

$$f(\alpha) = \begin{cases} 1, 0 < \alpha < 1 \\ 0, \text{otherwise} \end{cases} \tag{5.2}$$

Consumers choose sustainable apparel if $u_2 > u_1$; otherwise, they choose traditional apparel. The competition between the two firms is modeled as a two-stage game. In the first stage, the sustainable apparel firm determines the level of sustainability for its product. In the second stage, both firms simultaneously compete in the product market by setting prices.

5.2.2. Model Assumptions

Assumption 1: The additional utility Δu derived from sustainable apparel is positively correlated with the product's sustainability level. Specifically, $\Delta u = \theta s$, where θ represents the degree of consumer environmental awareness, and s denotes the sustainability level of the product.

Assumption 2: Traditional and sustainable apparel are identical in terms of appearance, function, and comfort. The only difference lies in their environmental impact—sustainable apparel imposes less environmental harm. Consumers exhibit exclusive purchase behavior, meaning they will buy only one type of apparel or none at all.

Assumption 3: Environmentally conscious consumers derive greater utility from purchasing sustainable apparel than from traditional alternatives, hence showing a preference for the former.

Assumption 4: The unit production cost of traditional apparel is c. The unit production cost of sustainable apparel is $c + \delta s$, where δ is the marginal cost coefficient associated with the sustainability level, it is assumed that $0 \leq \delta < 2\theta$.

Assumption 5: To enhance sustainability, apparel firms must invest in technological R&D. The one-time R&D cost is given by $\frac{s^2}{2}$.

Assumption 6: The government provides subsidies based on the product's sustainability level. The subsidy rate is γ, implying that each unit of sustainability earns a subsidy of γs. The relevant parameters are presented in Table 5.1, and the research framework of this study is illustrated in Fig. 5.1.

Table 5.1.

Description of model parameters and symbols

Symbol	Definition
u_0	Basic utility derived from meeting general consumer needs
u_1/u_2	Net utility from purchasing traditional apparel / sustainable apparel
Δu	Additional utility provided by sustainable apparel
α	Consumer sensitivity to the additional utility of sustainable apparel
γ	Government subsidy rate per unit of sustainability
θ	Degree of consumer environmental awareness
δ	Marginal cost coefficient for sustainability in sustainable apparel
c	Unit production cost of traditional apparel
s	Sustainability level of sustainable apparel
q_1/q_2	Market share of traditional apparel / sustainable apparel
p_1/p_2	Market price of traditional apparel / sustainable apparel
π	Profit of the apparel manufacturing firm

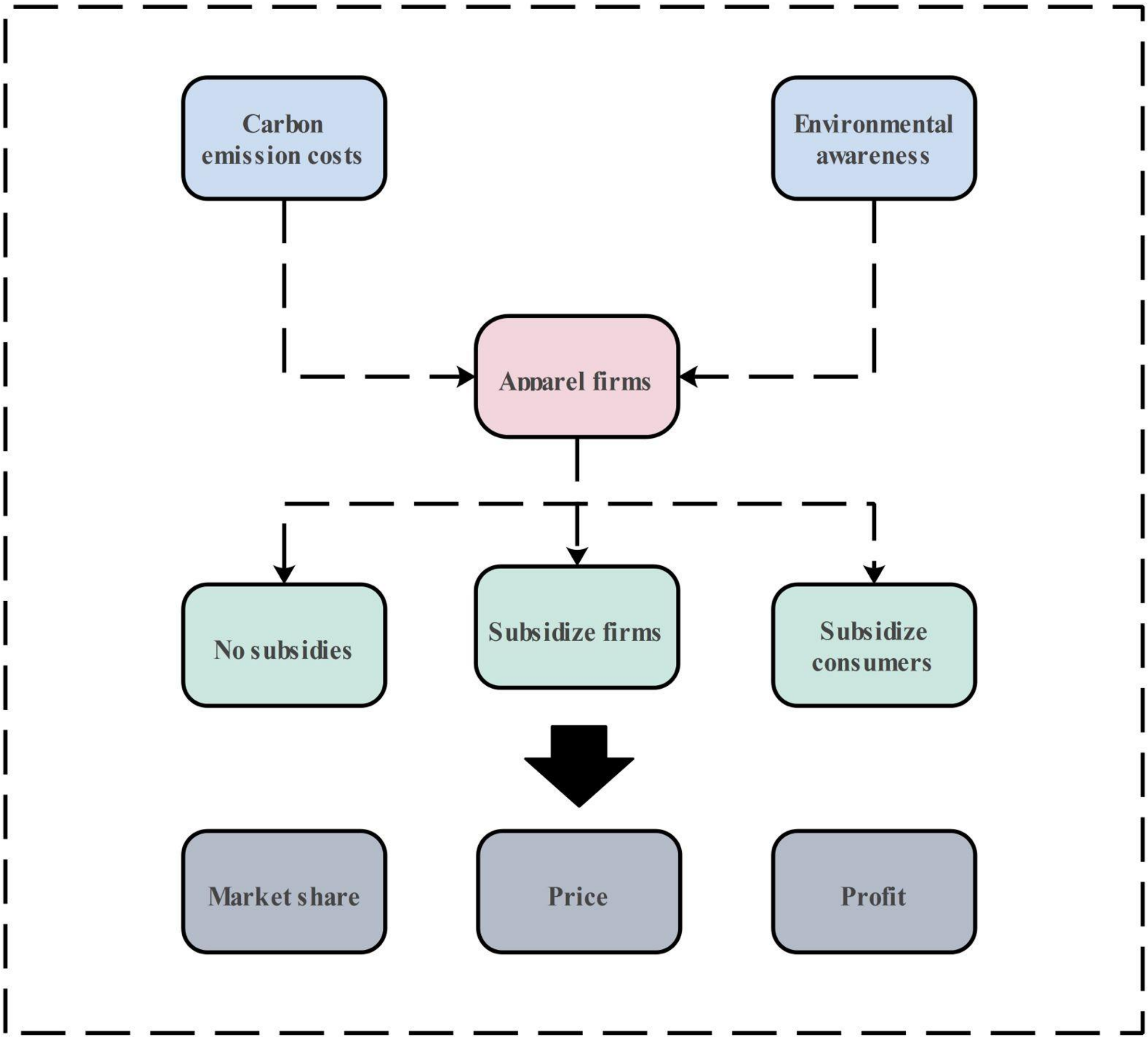


Fig. 5.1. Research framework

5.3. Competitive model

5.3.1. Model without government subsidy

From Equation (5.1), consumers will choose traditional apparel when $\alpha < \frac{p_2 - p_1}{\Delta u}$, and sustainable apparel when $\alpha > \frac{p_2 - p_1}{\Delta u}$.

From Equation (5.2), the market shares of traditional and sustainable apparel are:

$$\begin{cases} q_1 = \int_0^{\frac{p_2-p_1}{\Delta u}} f(\alpha)\, d\alpha = \frac{p_2-p_1}{\theta s} \\ q_2 = \int_{\frac{p_2-p_1}{\Delta u}}^{1} f(\alpha)\, d\alpha = \frac{\theta s - p_2 + p_1}{\theta s} \end{cases} \tag{5.3}$$

Hence, the profit functions of the traditional and sustainable apparel firms are:

$$\begin{cases} \pi_1 = (p_1 - c)\frac{p_2-p_1}{\theta s} \\ \pi_2 = (p_2 - c - \delta s)\frac{\theta s - p_2 + p_1}{\theta s} - \frac{s^2}{2} \end{cases} \tag{5.4}$$

Take the partial derivative of π_1 and π_2 with respect to p_1 and p_2 , respectively, and setting them equal to zero, we obtain:

$$\begin{cases} p_1 = \frac{\theta s + 3c + \delta s}{3} \\ p_2 = \frac{2\theta s + 3c + 2\delta s}{3} \end{cases} \tag{5.5}$$

Substituting Equation (5.5) into Equation (5.4), taking the partial derivative of π_2 with respect to s, and setting it equal to zero, we obtain:

$$s^* = \frac{(2\theta - \delta)^2}{9\theta} \tag{5.6}$$

Taking the second-order partial derivative of π_2 with respect to s yields $\frac{\partial^2 \pi_2}{\partial s^2} < 0$, indicating that s^* is indeed the optimal sustainability level. Substituting this value into Equation (5.5) yields the equilibrium prices of traditional and sustainable apparel:

$$\begin{cases} p_1^* = c + \frac{(2\theta-\delta)^2(\theta+\delta)}{27\theta} \\ p_2^* = c + \frac{(2\theta-\delta)^2(2\theta+2\delta)}{27\theta} \end{cases} \tag{5.7}$$

Thus, the sustainability premium is:

$$p_2^* - p_1^* = \frac{(2\theta-\delta)^2(\theta+\delta)}{27\theta} \tag{5.8}$$

Taking the partial derivatives of p_1^*, p_2^*, and $p_2^* - p_1^*$ with respect to θ yields $\frac{\partial p_1^*}{\partial \theta} > 0$, $\frac{\partial p_2^*}{\partial \theta} > 0$, $\frac{\partial (p_2^* - p_1^*)}{\partial \theta} > 0$, indicating that rising environmental awareness increases the prices of both types of apparel as well as the price premium, with a more pronounced effect on sustainable apparel. This result stems from the differences in pricing mechanisms between the two types of products: heightened environmental awareness increases consumers' perceived utility from purchasing sustainable apparel, thereby raising their willingness to pay. In contrast, the price increase in traditional apparel is primarily driven by the substitution effect—i.e., the rising price of sustainable apparel induces an upward adjustment in the relative price of traditional apparel.

Substituting Equation (5.7) into Equation (5.3), we obtain the equilibrium market shares:

$$\begin{cases} q_1^* = \frac{\theta+\delta}{3\theta} \\ q_2^* = \frac{2\theta-\delta}{3\theta} \end{cases} \tag{5.9}$$

Taking the partial derivatives of q_1^* and q_2^* with respect to θ yields $\frac{\partial q_1^*}{\partial \theta} < 0$, $\frac{\partial q_2^*}{\partial \theta} > 0$, indicating that as consumer environmental awareness increases, preference for sustainable apparel strengthens, leading to a decline in the market share of traditional apparel and a rise in that of sustainable apparel. Similarly, taking the partial derivatives of q_1^* and q_2^* with respect to δ gives $\frac{\partial q_1^*}{\partial \delta} > 0$, $\frac{\partial q_2^*}{\partial \delta} < 0$, suggesting that an increase in the unit cost coefficient of sustainable apparel reduces its competitiveness, prompting consumers to shift preference toward traditional apparel and thereby decreasing demand for sustainable apparel. In summary, consumer environmental awareness and the unit cost coefficient of sustainable apparel are key determinants of the market share of the two types of apparel. However, if the unit cost of sustainable apparel remains high, sustainable products may still struggle to gain a competitive advantage in the market, even when consumers possess a certain level of environmental awareness. To address this issue, it is necessary, on one hand, to encourage firms to increase R&D investment and enhance sustainable technological capabilities to reduce production costs and improve product competitiveness; on the other hand, policy tools such as government subsidies can be employed to lower the unit production cost of sustainable apparel. A detailed analysis of government subsidies will be presented in the following sections.

Substituting Equations (5.7) and (5.9) into Equation (5.4), we derive the equilibrium profits:

$$\begin{cases} \pi_1^* = \dfrac{(2\theta-\delta)^2(\theta+\delta)^2}{81\lambda^2} \\ \pi_2^* = \dfrac{(2\theta-\delta)^4}{162\theta^2} \end{cases} \tag{5.10}$$

Taking the partial derivatives of π_1 and π_2 with respect to θ yields $\frac{\partial \pi_1^*}{\partial \theta} > 0$ and $\frac{\partial \pi_2^*}{\partial \theta} > 0$, indicating that increased environmental awareness enhances the market appeal of sustainable apparel, allowing sustainable firms to earn higher profits. Meanwhile, due to the substitution effect, traditional apparel can raise its price accordingly and also achieve greater profitability. Taking the partial derivatives of π_1 and π_2 with respect to δ yields $\frac{\partial \pi_1^*}{\partial \delta} < 0$ and $\frac{\partial \pi_2^*}{\partial \delta} < 0$, suggesting that rising unit costs undermine the competitiveness of sustainable apparel and suppress the profitability of both firms.

5.3.2. Model with government subsidy to sustainable apparel firms

The previous section analyzed how the marginal cost coefficient of sustainability and environmental awareness affect apparel firms in the absence of government subsidies. This section further investigates the impact of government subsidies on market equilibrium. Suppose the government provides a subsidy rate γ, per unit of sustainability. That is, for each unit increase in sustainability level s, the sustainable apparel firm receives a subsidy of γs. Under this condition, the profit functions of the two firms are:

$$\begin{cases} \pi_1^f = (p_1 - c)\frac{p_2 - p_1}{\theta s} \\ \pi_2^f = (p_2 - c - \delta s + \gamma s)\frac{\theta s - p_2 + p_1}{\theta s} - \frac{s^2}{2} \end{cases} \tag{5.11}$$

At this point, the optimal sustainability level under subsidy is:

$$s^{f*} = \frac{(2\theta - \delta + \gamma)^2}{9\theta} \tag{5.12}$$

The equilibrium prices of traditional and sustainable apparel are:

$$\begin{cases} p_1^{f*} = c + \frac{(\theta + \delta - \gamma)(2\theta - \delta + \gamma)^2}{27\theta} \\ p_2^{f*} = c + \frac{2(\theta + \delta - \gamma)(2\theta - \delta + \gamma)^2}{27\theta} \end{cases} \tag{5.13}$$

The equilibrium market shares of traditional and sustainable apparel are:

$$\begin{cases} q_1^{f*} = \frac{(\theta+\delta-\gamma)}{3\theta} \\ q_2^{f*} = \frac{2\theta-\delta+\gamma}{3\theta} \end{cases} \tag{5.14}$$

The equilibrium profits of traditional and sustainable apparel firms are:

$$\begin{cases} \pi_1^{f*} = \frac{(\theta+\delta-\gamma)^2(2\theta-\delta+\gamma)^2}{81\theta^2} \\ \pi_2^{f*} = \frac{(2\theta-\delta+\gamma)^4}{162\theta^2} \end{cases} \tag{5.15}$$

Clearly, $s^{f*} > s^*$, indicating that government subsidies to apparel producers can incentivize firms to increase investment in sustainable technologies and enhance the sustainability level of sustainable apparel.

We now proceed to analyze the effect of government subsidies on market equilibrium, Taking the partial derivative of s^{f*} with respect to γ yields:

$$\frac{\partial s^{f*}}{\partial \gamma} = \frac{2(2\theta - \delta + \gamma)}{9\theta}$$

Given that $0 \leq \delta < 2\theta$, it follows that $\frac{\partial s^{f*}}{\partial \gamma} > 0$, indicating that an increase in subsidy incentivizes firms to enhance the sustainability level of their products.

Taking the partial derivative of p_1^{f*} with respect to γ yields:

$$\frac{\partial p_1^{f*}}{\partial \gamma} = \frac{(2\theta - \delta + \gamma)(\delta - \gamma)}{9\theta}$$

When $\gamma < \delta$, $\frac{\partial p_1^{f*}}{\partial \gamma} > 0$;

When $\gamma > \delta$, $\frac{\partial p_1^{f*}}{\partial \gamma} < 0$.

Taking the partial derivative of p_2^{f*} with respect to γ yields:

$$\frac{\partial p_2^{f*}}{\partial \gamma} = \frac{2(2\theta - \delta + \gamma)(\delta - \gamma)}{9\theta}$$

When $\gamma < \delta, \frac{\partial p_2^{f*}}{\partial \gamma} > 0$;

When $\gamma > \delta, \frac{\partial p_2^{f*}}{\partial \gamma} < 0$.

It can be observed that when $\gamma < \delta$, an increase in subsidies leads to a rise in the price of sustainable apparel. This occurs because the subsidy intensity is insufficient to fully offset the marginal cost increase associated with higher sustainability levels, thereby preventing sustainable apparel from achieving a price advantage. In addition, the price of traditional apparel also increases due to the substitution effect. When $\gamma > \delta$, the prices of both types of apparel decrease. In this case, the subsidy intensity exceeds the marginal cost increase resulting from enhanced sustainability, enabling firms to improve the sustainability of their products while simultaneously reducing the price of sustainable apparel. As a result, the effect of government subsidies is fully realized.

Taking the partial derivatives of q_1^{f*} and q_2^{f*} with respect to γ yields:

$$\frac{\partial q_1^{f*}}{\partial \gamma} = -\frac{1}{3\theta} < 0$$

$$\frac{\partial q_2^{f*}}{\partial \gamma} = \frac{1}{3\theta} > 0$$

This result implies that increased subsidies reduce the unit cost of sustainable apparel, making it more attractive in terms of price and performance, thus increasing its market share. However, due to substitution effects, the market share of traditional apparel declines accordingly.

Taking the partial derivative of π_2^{f*} with respect to γ yields:

$$\frac{\partial \pi_2^{f*}}{\partial \gamma} = \frac{4(2\theta - \delta + \gamma)^3}{162\theta^2} > 0$$

It can be inferred that higher government subsidies lead to increased profits for sustainable apparel firms.

Taking the partial derivative of π_1^{f*} with respect to γ yields:

$$\frac{\partial \pi_1^{f*}}{\partial \gamma} = \frac{2(\theta + \delta - \gamma)(2\theta - \delta + \gamma)(-\theta + 2\delta - 2\gamma)}{81\theta^2}$$

When $q_1^{f*} > q_2^{f*}$, $(-\theta + 2\delta - 2\gamma) > 0$, and thus $\frac{\partial \pi_1^{f*}}{\partial \gamma} > 0$. This is because traditional apparel firms dominate the market under this condition, consumers are price-sensitive, and the subsidy has a limited effect on stimulating demand for sustainable products. Traditional apparel firms can offset demand losses through minor price reductions and indirectly benefit from supply chain externalities caused by subsidies via a free-rider effect, resulting in a positive correlation between their profits and the subsidy level. When $q_1^{f*} < q_2^{f*}$, $(-\theta + 2\delta - 2\gamma) < 0$, and therefore $\frac{\partial \pi_1^{f*}}{\partial \gamma} < 0$. This is because in this scenario, sustainable apparel firms dominate the market and already benefit from economies of scale, with the subsidy policy significantly amplifying their competitive advantage. Meanwhile, traditional apparel firms fall into a price-reduction inefficacy trap, as even substantial price cuts fail to shift consumer preference away from subsidized sustainable products, leading to a continuous decline in market share and profits as the subsidy level increases. As a result, there is a negative correlation between subsidies and profits for traditional apparel firms.

The above analysis indicates that market structure plays a critical moderating role in shaping the effectiveness of government subsidy policies. Specifically, the impact of subsidies on traditional firms' profitability is significantly constrained by their market position. Therefore, subsidy policies should be designed with full consideration of the competitive landscape and the strategic position of firms, in order to ensure targeted and effective policy outcomes.

5.3.3. Model with government subsidy to consumers

In addition to subsidizing apparel firms, the government may also opt to directly subsidize consumers. In this case, the utility derived by consumers from purchasing sustainable apparel changes as follows:

$$\begin{cases} u_1 = u_0 - p_1 \\ u_2 = u_0 + \alpha\Delta u - p_2 + \gamma s \end{cases} \tag{5.16}$$

Consumers will choose traditional apparel when $\theta < \frac{p_2 - p_1 - \gamma s}{\Delta u}$, and sustainable apparel when $\theta > \frac{p_2 - p_1 - \gamma s}{\Delta u}$.

At this point, the optimal sustainability level under subsidy is:

$$s^{C*} = \frac{(2\theta - \delta + \gamma)^2}{9\theta} \tag{5.17}$$

Under this setting, the equilibrium prices of traditional and sustainable apparel are:

$$\begin{cases} p_1^{c*} = c + \frac{(\theta+\delta-\gamma)(2\theta-\delta+\gamma)^2}{27\theta} \\ p_2^{c*} = c + \frac{(2\theta+2\delta+\gamma)(2\theta-\delta+\gamma)^2}{27\theta} \end{cases} \tag{5.18}$$

The equilibrium market shares of traditional and sustainable apparel are:

$$\begin{cases} q_1^{c*} = \frac{(\theta+\delta-\gamma)}{3\theta} \\ q_2^{c*} = \frac{2\theta-\delta+\gamma}{3\theta} \end{cases} \tag{5.19}$$

The equilibrium profits of traditional and sustainable apparel firms are:

$$\begin{cases} \pi_1^{c*} = \frac{(\theta+\delta-\gamma)^2(2\theta-\delta+\gamma)^2}{81\theta^2} \\ \pi_2^{c*} = \frac{(2\theta-\delta+\gamma)^4}{162\theta^2} \end{cases} \tag{5.20}$$

We next analyze the impact of consumer-side subsidies. Taking the partial derivative of s^{c*} with respect to γ yields:

$$\frac{\partial s^{c*}}{\partial \gamma} = \frac{2(2\theta - \delta + \gamma)}{9\theta}$$

Given $0 \leq \delta < 2\theta$, it follows that $\frac{\partial s^{c*}}{\partial \gamma} > 0$. This indicates that higher government subsidies to consumers increase their willingness to pay a premium for sustainable apparel and encourage firms to invest more in R&D.

Taking the partial derivative of p_1^{c*} with respect to γ yields:

$$\frac{\partial p_1^{c*}}{\partial \gamma} = \frac{(2\theta - \delta + \gamma)(\delta - \gamma)}{9\theta}$$

When $\gamma < \delta$, $\frac{\partial p_1^{c*}}{\partial \gamma} > 0$;

When $\gamma > \delta, \frac{\partial p_1^{c*}}{\partial \gamma} < 0$.

Taking the partial derivative of p_2^{c*} with respect to γ yields:

$$\frac{\partial p_2^{c*}}{\partial \gamma} = \frac{(2\theta - \delta + \gamma)(2\theta + \delta + \gamma)}{9\theta} > 0$$

It can be concluded that consumer subsidies consistently lead to an increase in the price of sustainable apparel. When $\gamma < \delta$, low levels of subsidies exert limited influence on the demand for sustainable apparel. Due to the substitution effect, the increase in the price of sustainable apparel simultaneously drives up the price of traditional apparel, resulting in a coordinated price increase. When $\gamma > \delta$, high levels of subsidies significantly reduce the relative price of sustainable apparel, thereby enhancing its market competitiveness. In this scenario, traditional apparel firms, in an effort to prevent substantial market share loss, are forced to adopt price-cutting strategies as a form of defensive competition. As a result, the price of sustainable apparel increases while that of traditional apparel decreases.

By comparing the effects of the two subsidy schemes, we find that: $s^{c*} = s^{f*}$, $p_1^{c*} = p_1^{f*}$, $q_1^{c*} = q_1^{f*}$, $q_2^{c*} = q_2^{f*}$, $\pi_1^{c*} = \pi_1^{f*}$, $\pi_2^{c*} = \pi_2^{f*}$, $p_2^{c*} > p_2^{f*}$. This indicates that the two subsidy approaches do not affect the sustainability level, market shares, or firm profits. However, consumer-side subsidies lead to higher prices for sustainable apparel. This is because such subsidies increase the utility derived by consumers, enhancing their willingness to pay. In contrast, firm-side subsidies reduce production costs, encouraging firms to lower prices.

We now compare the social welfare outcomes under both subsidy schemes:

Social welfare = Consumer welfare + Firm welfare

Since $\pi_1^{c*} = \pi_1^{f*}$, $\pi_2^{c*} = \pi_2^{f*}$, firm welfare are identical under both schemes.

Under firm-side subsidies, consumer surplus is:

$$cs^f = \left(u_0 - p_1^{f*}\right)q_1^{f*} + \left(u_0 + \Delta u\alpha - p_2^{f*}\right)q_2^{f*}$$

Under consumer-side subsidies, consumer surplus is:

$$cs^c = (u_0 - p_1^{c*})q_1^{c*} + (u_0 + \Delta u\alpha - p_2^{c*} + \gamma s^{c*})q_2^{c*}$$

Solving both yields:

$$cs^f = cs^c = u_0 - c + \frac{(2\theta - \delta + \gamma)^3\alpha}{27\theta} - \frac{(2\theta-\delta+\gamma)^2(\theta+\delta-\gamma)^2 - 2(\theta+\delta-\gamma)(2\theta-\delta+\gamma)^3}{81\theta^2} \tag{5.21}$$

Therefore, the two subsidy schemes yield identical consumer welfare, resulting in the same level of overall social welfare. Although the two subsidy schemes lead to identical social welfare in theory, several practical factors may cause differences in real-world implementation: Subsidizing firms are generally easier to administer and monitor, whereas providing subsidies to consumers involves more complex procedures, such as eligibility verification and distribution channels, which lead to differing administrative costs. Moreover, firms may fail to allocate subsidies toward production or price reductions, thereby significantly undermining consumer welfare. This indicates that in an idealized game-theoretic model, the identity of the subsidy recipient does not alter the equilibrium outcome. However, when real-world factors are taken into account, the choice of subsidy scheme may lead to different practical outcomes.

5.4. Numerical simulation

To further analyze the impact of consumer environmental awareness and government subsidies on the prices, profits, and market shares of traditional and sustainable apparel, this section conducts simulation analysis using MATLAB software.

5.4.1. Impact of consumer environmental awareness

5.4.1.1. Effect of consumer environmental awareness on apparel pricing

Figs 5.2 to 5.4 illustrate the influence of consumer environmental awareness on the pricing of traditional and sustainable apparel. The baseline parameter settings are as follows:

c = 1; δ = 0.5; γ = 0.3; θ _min = 0.4; θ _max = 2; num_points = 200.

Fig. 5.2 illustrates how the prices of traditional and sustainable apparel, as well as their price differentials, evolve with changes in consumer environmental awareness under the scenario where the government provides subsidies to sustainable apparel enterprises. As consumers become more environmentally conscious, their recognition of sustainability attributes in apparel increases, enhancing their willingness to pay and thereby driving the price of sustainable apparel upward. For traditional apparel, the rising price of sustainable alternatives creates a relative price advantage due to substitution effects, prompting traditional apparel producers to raise prices in an attempt to maintain overall profits. Moreover, the price gap between sustainable and traditional apparel shows a gradually widening trend. This is primarily because the increase in consumers' willingness to pay for sustainable apparel is more pronounced, leading them to accept a higher premium. In contrast, lacking sustainable attributes, the pricing of traditional apparel relies more on market-driven mechanisms, making it difficult to keep pace with the price growth of sustainable options, thereby further widening the price gap.

Fig 5.3 depicts the evolution of equilibrium prices and price differentials between traditional and sustainable apparel in response to changes in consumer environmental awareness, under the scenario where the government subsidizes consumers directly. As environmental awareness rises, consumers become more willing to accept the premium on sustainable apparel. Combined with subsidies that directly enhance their purchasing power, this further accelerates the upward trend in sustainable apparel prices. The price of traditional apparel may also undergo slight adjustments in response to competitive market strategies. Unlike firm-based subsidies, this approach enhances actual consumer willingness to pay from the demand side, converting subsidies into higher prices and thereby further widening the price gap with traditional apparel.

Fig 5.4 presents a comparative analysis of how sustainable apparel prices change with environmental awareness under the two different subsidy schemes. As environmental awareness continues to rise, sustainable apparel prices under both subsidy scenarios exhibit an upward trend, though with markedly different rates of increase. Notably, under the consumer subsidy model, the price curve rises more steeply, indicating greater price elasticity. This suggests that when subsidies are directed at enhancing consumer purchasing power, firms are more inclined to increase product prices to capture the additional willingness to pay, thereby achieving higher revenues. In contrast, under the firm subsidy model, subsidies are primarily used to alleviate the marginal cost pressures of sustainable production, thereby promoting supply-side expansion of sustainable apparel. Although this approach also contributes to price increases, its effect on final market prices is relatively limited, as it essentially aims to reduce production costs.

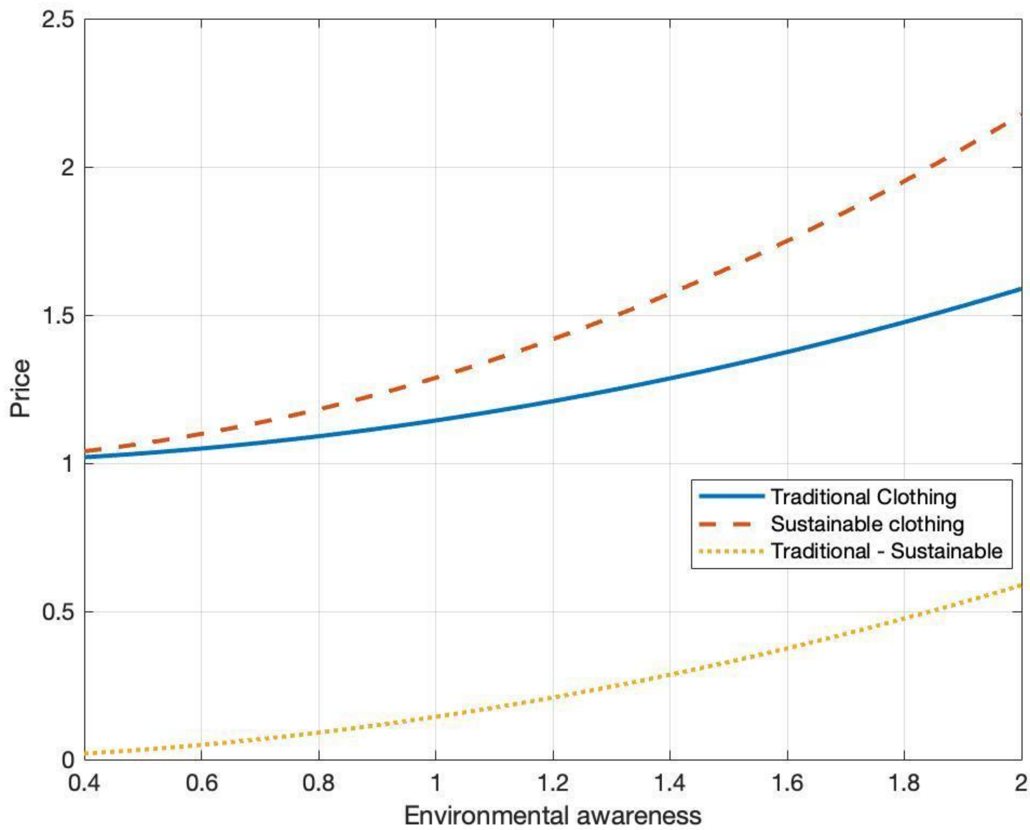


Fig 5.2: Impact of environmental awareness under firm-side subsidies for sustainable apparel.

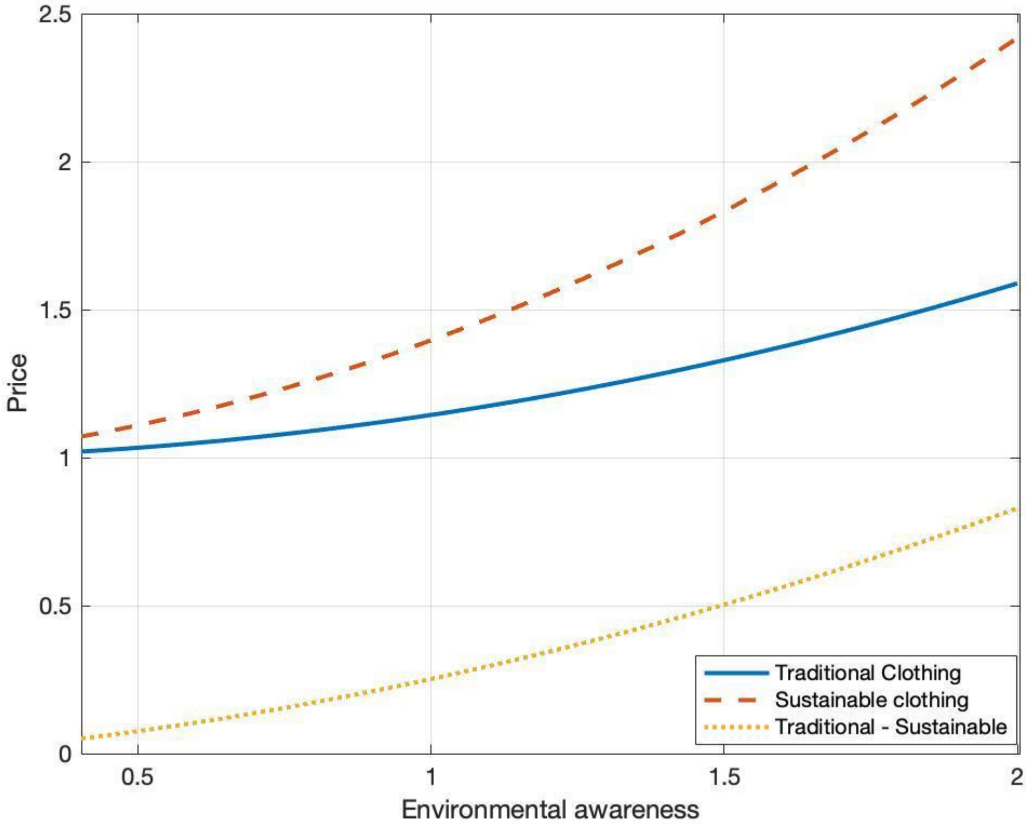


Fig 5.3: Impact of environmental awareness under consumer-side subsidies for sustainable apparel.

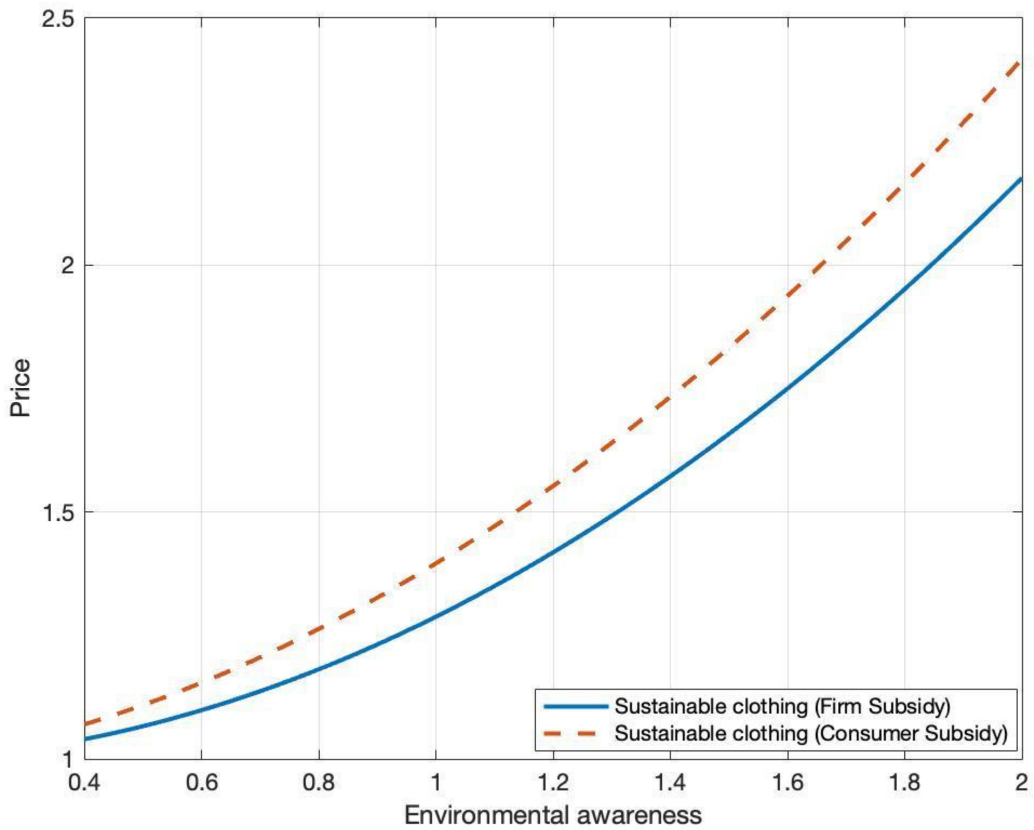


Fig 5.4: Comparison of sustainable apparel prices under two government subsidy schemes.

5.4.1.2. Effect of consumer environmental awareness on market share

Fig 5 illustrates how the market shares of traditional and sustainable apparel evolve with changes in consumer environmental awareness under the scenario where the government subsidizes sustainable apparel enterprises. Under the influence of the subsidy mechanism, the production costs of sustainable apparel are significantly reduced, allowing firms to offer these products at more competitive prices. As consumers become more environmentally aware, their emphasis on product sustainability continues to rise, further enhancing the market acceptance and penetration of sustainable apparel.

Consequently, the market share of sustainable apparel increases steadily. Meanwhile, due to the lack of sustainability advantages, the market share of traditional apparel shows a gradual decline amid shifting consumer preferences.

Fig 5.6 shows how the market shares of traditional and sustainable apparel change with increasing environmental awareness when the government provides subsidies directly to consumers. Under this subsidy mechanism, the policy focus shifts from the supply side to the demand side, directly enhancing consumers' effective purchasing power for sustainable apparel. As environmental awareness increases, consumers’ recognition of sustainable products improves. Combined with enhanced price accessibility due to subsidies, sustainable apparel continues to gain market share even at higher prices. Accordingly, the market share of traditional apparel declines, reflecting the ongoing crowding-out effect of consumer transition on the traditional market.

Fig 5.7 presents a comparison of the market share changes resulting from government subsidies provided to firms versus consumers. The results indicate that both subsidy mechanisms are equally effective in enhancing the market competitiveness of sustainable apparel. On one hand, subsidies to firms enhance supply capacity by reducing the production costs of sustainable apparel; on the other hand, subsidies to consumers increase demand by improving their purchasing power. Both approaches contribute to the improvement of sustainable apparel market competitiveness through distinct pathways.

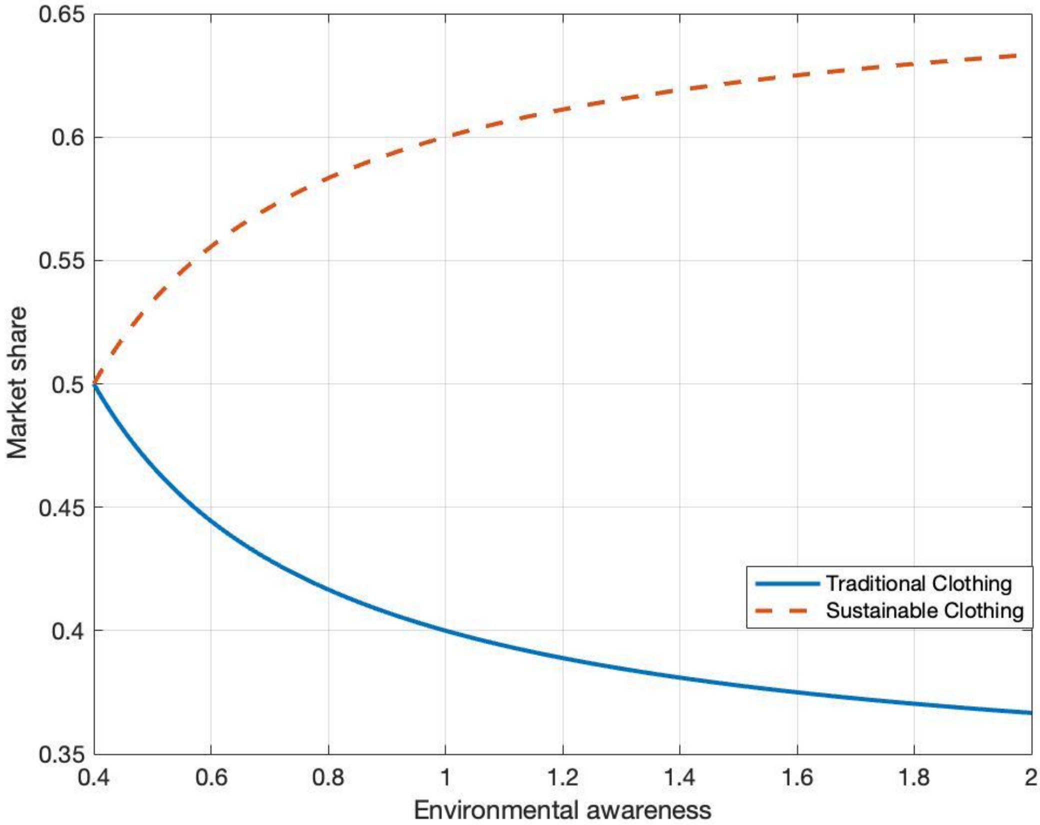


Fig 5.5: Impact of environmental awareness on market share under firm-side subsidies.

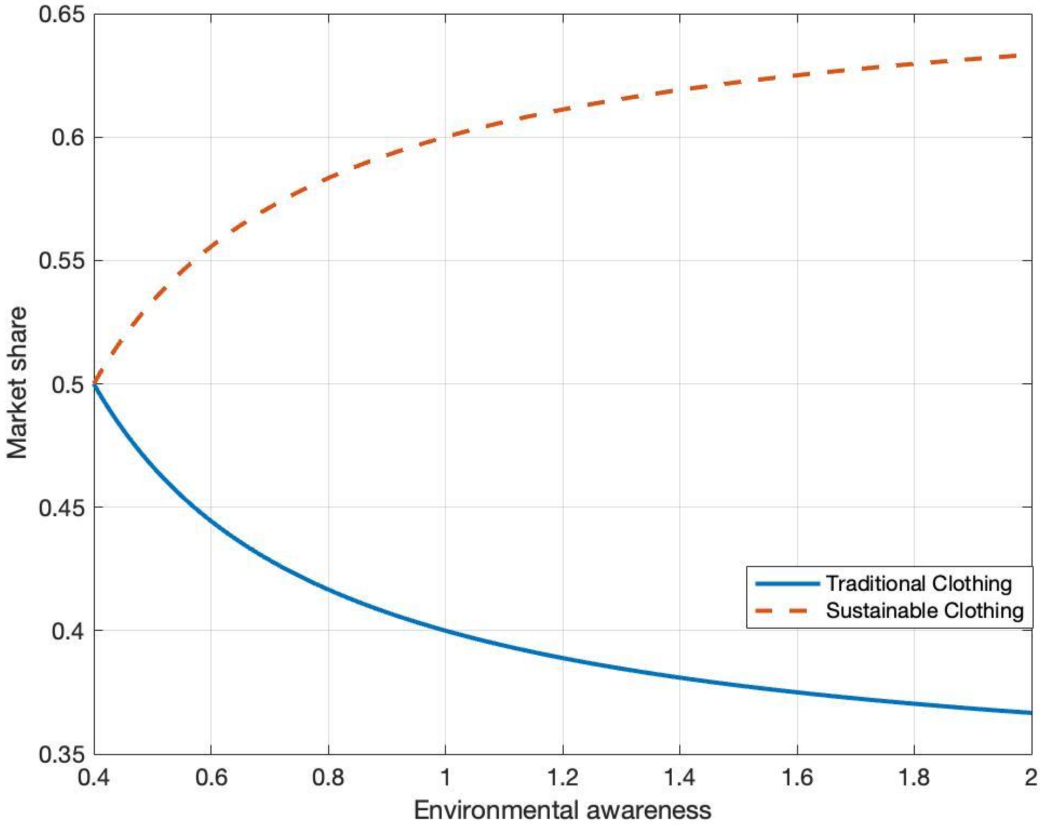


Fig 5.6: Impact of environmental awareness on market share under consumer-side subsidies.

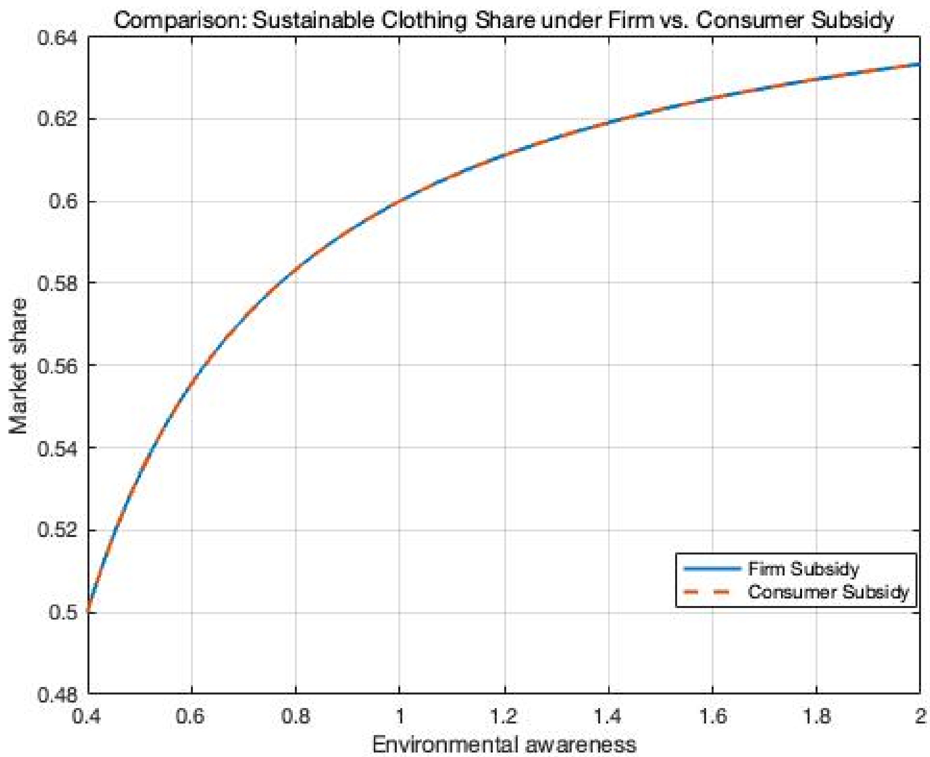


Fig 5.7: Impact of two government subsidy schemes on market share.

5.4.1.3. Effect of consumer environmental awareness on firm profits

Fig 5.8 illustrates how the profits of traditional and sustainable apparel firms evolve with changes in consumer environmental awareness under the scenario where the government subsidizes sustainable apparel enterprises. Under this subsidy mechanism, sustainable apparel firms receive per-unit sustainability subsidies, which effectively alleviate the marginal cost pressure associated with enhancing product sustainability. Combined with the continuous rise in consumer environmental awareness, sustainable products enjoy both price and performance advantages in the market, resulting in steadily increasing profit levels. The profits of traditional apparel firms also increase with growing consumer environmental awareness. This is because, as the price of sustainable apparel rises, some marginal consumers—driven by price sensitivity—switch to traditional apparel, allowing these firms to implement limited price increases in the residual market and thereby boost profits.

Fig 5.9 depicts how the profits of traditional and sustainable apparel firms change in response to consumer environmental awareness when the government provides subsidies to consumers. Under this subsidy mechanism, the profits of sustainable apparel firms show a rapid upward trend. For traditional apparel firms, profits also increase, though the growth rate is significantly lower than that of sustainable apparel firms. The profit growth primarily stems from localized price adjustments in the residual market and retention of a portion of consumers.

Fig 5.10 presents a comparative analysis of how sustainable apparel firms' profits change with consumer environmental awareness under the two different subsidy mechanisms. The figure show that the two profit curves completely overlap, indicating a high degree of consistency in the quantitative effects of both subsidy approaches on the profit growth of sustainable apparel firms.

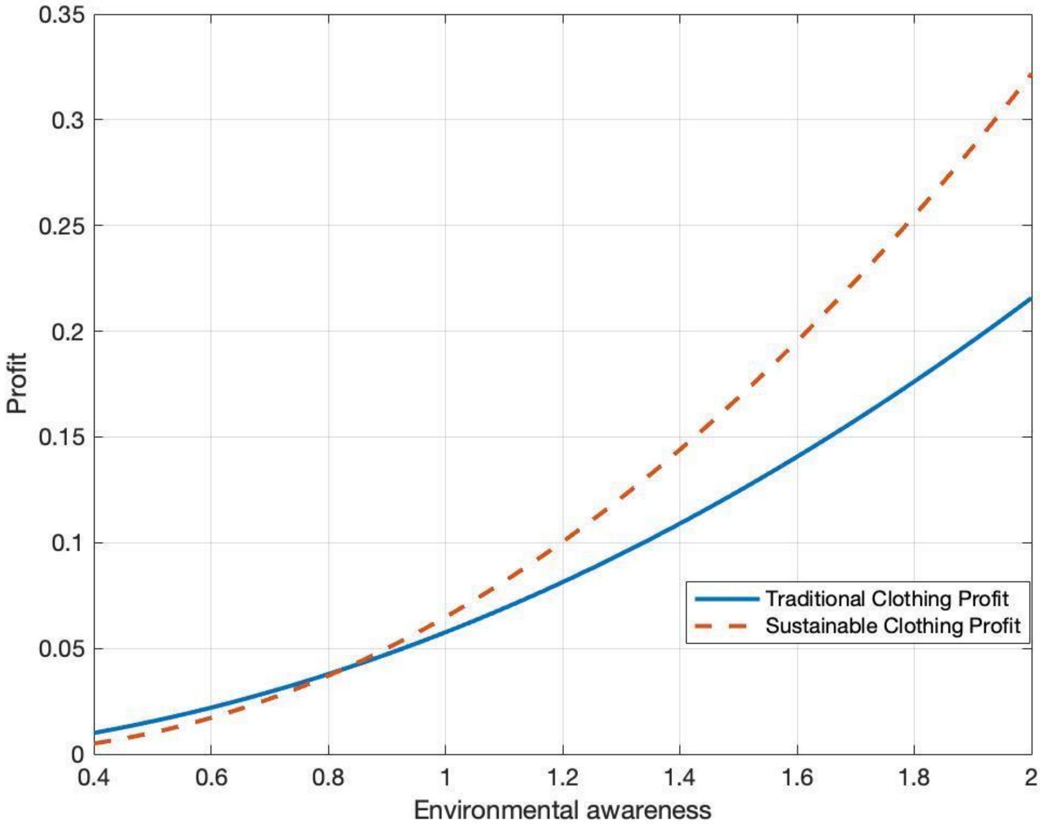


Fig 5.8: Impact of environmental awareness on profits under firm-side subsidy.

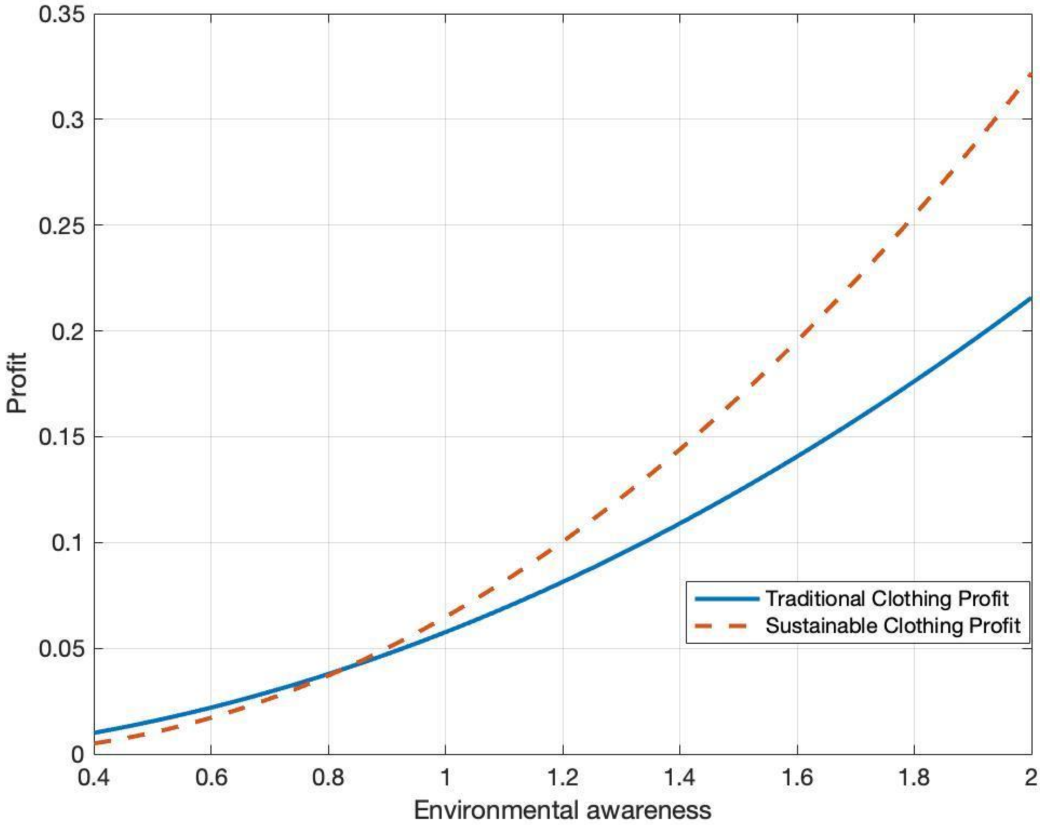


Fig 5.9: Impact of environmental awareness on profits under consumer-side subsidy.

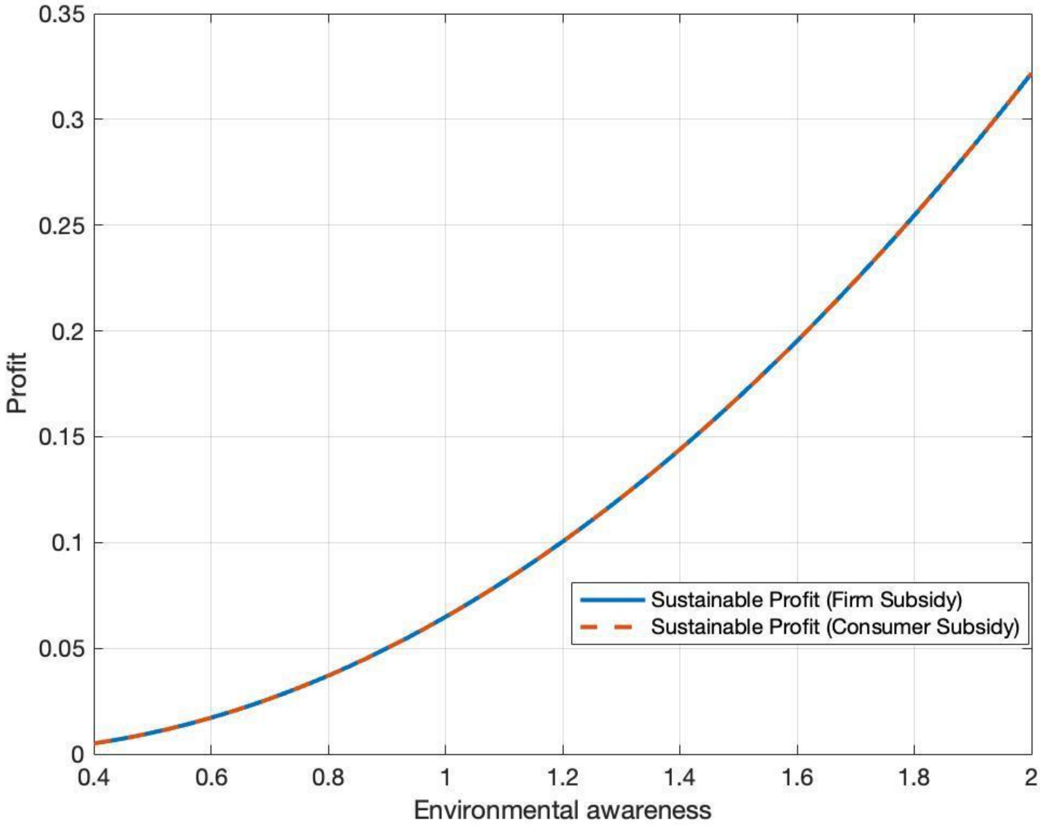


Fig 5.10: Impact of two government subsidy schemes on profit.

5.4.2. Impact of government subsidy intensity

5.4.2.1. Impact of government subsidy intensity on apparel pricing

This subsection analyzes the effects of government subsidy intensity on the prices of traditional and sustainable apparel. The simulation is conducted under the following baseline parameters:

c = 1; $\delta = 0.5$; $\theta = 0.6$; γ _min = 0; γ _max = 1; num_points = 200.

Fig 5.11 illustrates how the prices of traditional and sustainable apparel, as well as their price differentials, evolve with changes in subsidy intensity under the scenario where the government subsidizes sustainable apparel enterprises. As the subsidy intensity increases, the price of sustainable apparel first rises and then declines. In the initial stages, government incentives are insufficient to fully offset the marginal costs incurred by firms in enhancing sustainability. As a result, firms tend to pass the costs of R&D and sustainability investments onto product prices, leading to a temporary price increase. When the subsidy surpasses a critical threshold, the marginal subsidy effect exceeds the rate of cost increase, resulting in a substantial reduction in actual production costs. At this point, firms proactively reduce product prices, driving sustainable apparel into a declining price phase. The price of traditional apparel is influenced by market linkages and substitution effects. Thus, traditional apparel prices initially experience a moderate passive increase. However, as subsidy intensity grows and the cost-performance ratio of sustainable apparel improves, traditional apparel faces greater substitution pressure, leading to a subsequent price decline.

Fig 5.12 depicts how the prices of traditional and sustainable apparel and their price differentials evolve with varying subsidy levels under the scenario where the government provides subsidies to consumers. Under the consumer subsidy mechanism, subsidies directly enhance purchasing power. Sustainable apparel firms leverage this by strengthening their pricing strategies, converting increased willingness to pay into continually rising product prices. For traditional apparel, the price exhibits a rise-then-fall pattern. In the early phase of subsidies, some consumers—despite enhanced purchasing power—may remain in the traditional market due to price sensitivity, prompting a slight increase in traditional apparel prices. However, as subsidies intensify, the cost-performance advantage of sustainable apparel rapidly expands, causing a significant decline in demand for traditional apparel and a subsequent price drop. The price differential between the two types of apparel widens with increasing subsidy intensity, indicating that the consumer subsidy mechanism significantly intensifies market price segmentation, strengthens sustainable apparel's price leadership, and drives the market structure toward sustainability.

Fig 5.13 compares the evolution of sustainable apparel prices under varying subsidy intensities between enterprise and consumer subsidy mechanisms. Under the enterprise subsidy mechanism, the government incentivizes sustainable product supply by reducing production costs for firms. As subsidy intensity increases, firms initially face rising costs associated with sustainability improvements, leading to higher prices. Once the subsidy surpasses the marginal cost growth, costs drop significantly, prompting firms to lower prices to expand market share—resulting in a nonlinear "rise-then-fall" price pattern for sustainable apparel. In contrast, under the consumer subsidy mechanism, consumers' purchasing power and willingness to buy increase directly. Firms capitalize on this demand-side enhancement by raising prices to maximize profits, leading to a continuous upward trend in sustainable apparel prices as subsidies grow.

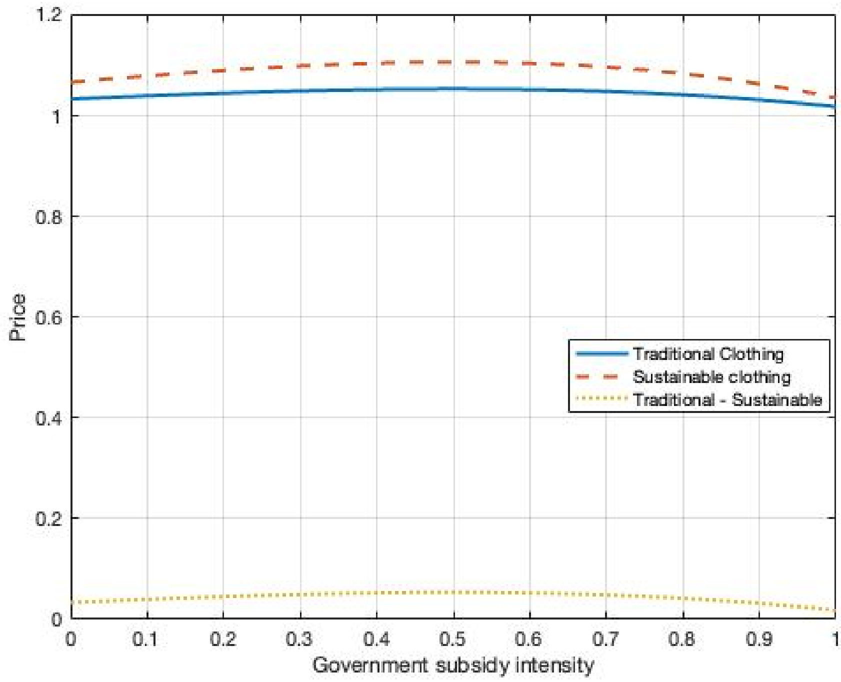


Fig 5.11: Impact of firm-side government subsidies on apparel prices.

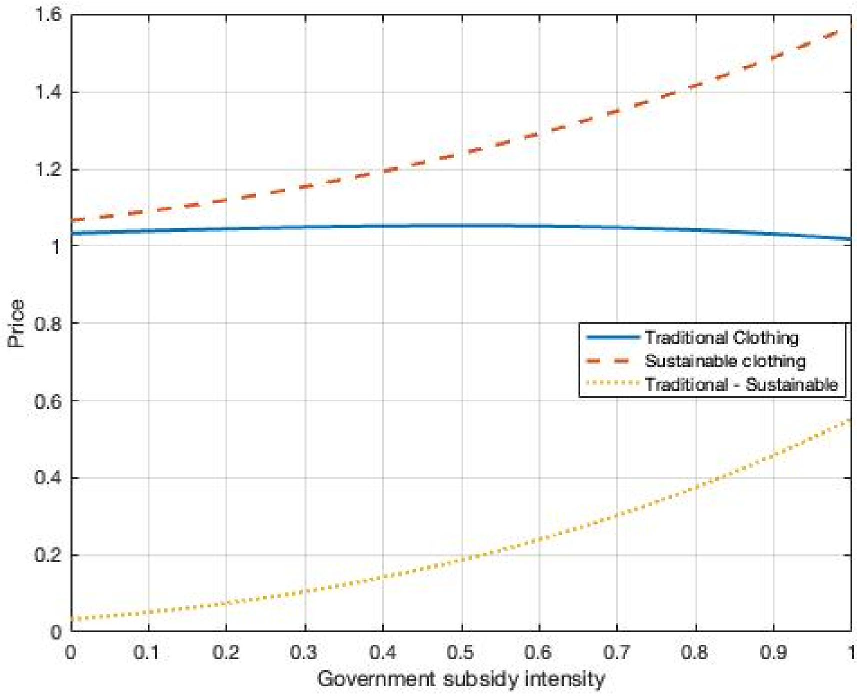


Fig 5.12: Impact of consumer-side government subsidies on apparel prices.

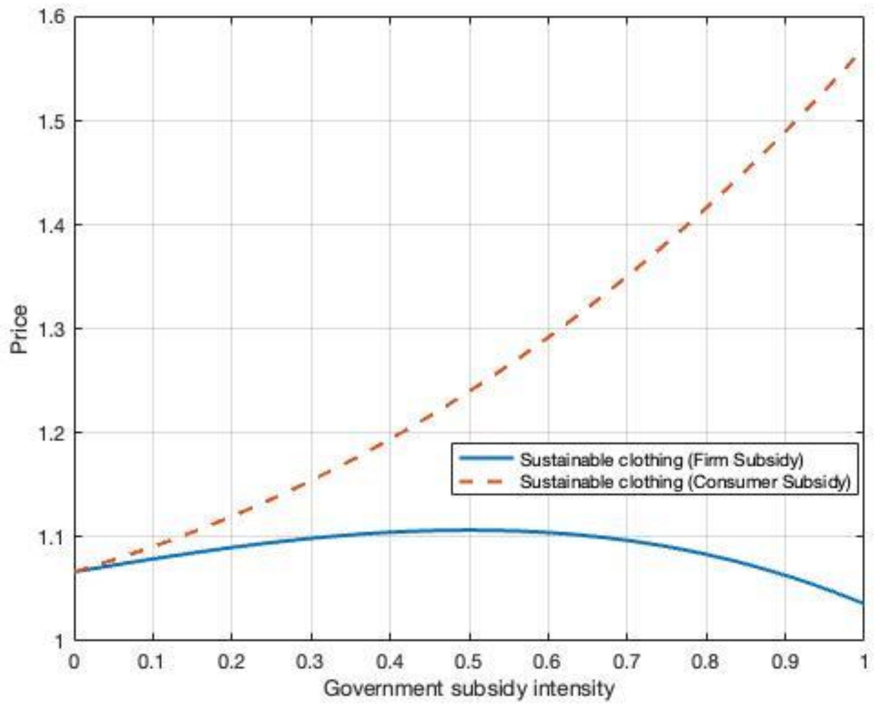


Fig 5.13: Comparison of sustainable apparel prices under two government subsidy schemes.

5.4.2.2. Impact of government subsidy intensity on market share

Figs 5.14 and 5.15 respectively illustrate how the market shares of traditional and sustainable apparel evolve with increasing subsidy intensity under scenarios where the government subsidizes sustainable apparel enterprises and consumers. As government subsidies intensify, the market share of sustainable apparel increases significantly, while that of traditional apparel gradually declines. This indicates that government subsidies, whether from the supply or demand side, effectively reshape market competition and promote a transformation in consumer behavior.

Fig 5.16 compares the evolution of sustainable apparel market share under varying subsidy intensities between enterprise and consumer subsidy mechanisms. The figure shows that the market share curves under both subsidy mechanisms nearly overlap, indicating numerical consistency in their effectiveness at increasing the market share of sustainable apparel, regardless of whether the subsidy targets the supply or demand side.

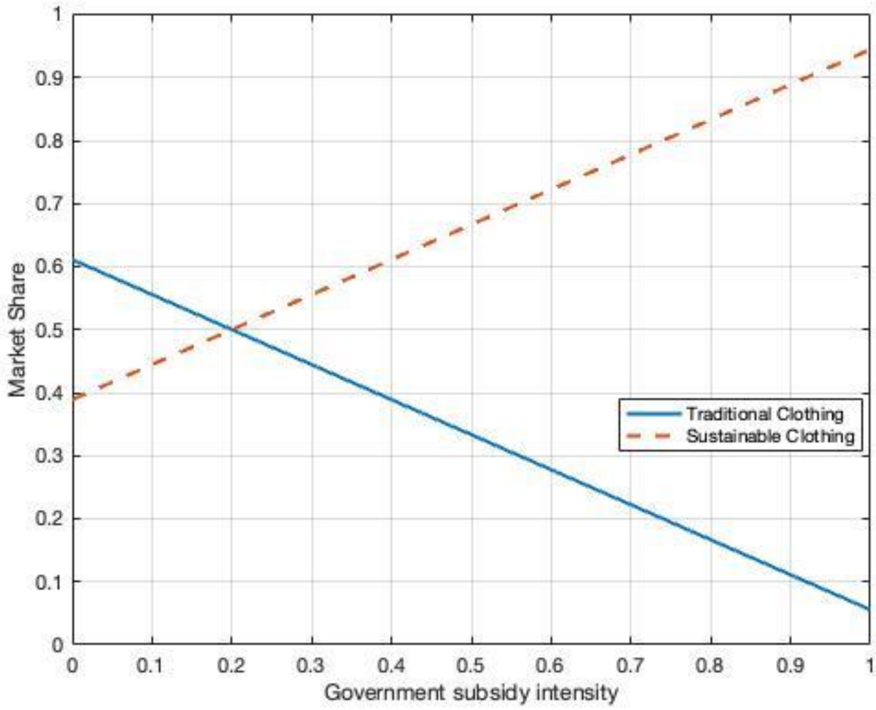


Fig 5.14: Impact of firm-side government subsidies on market shares.

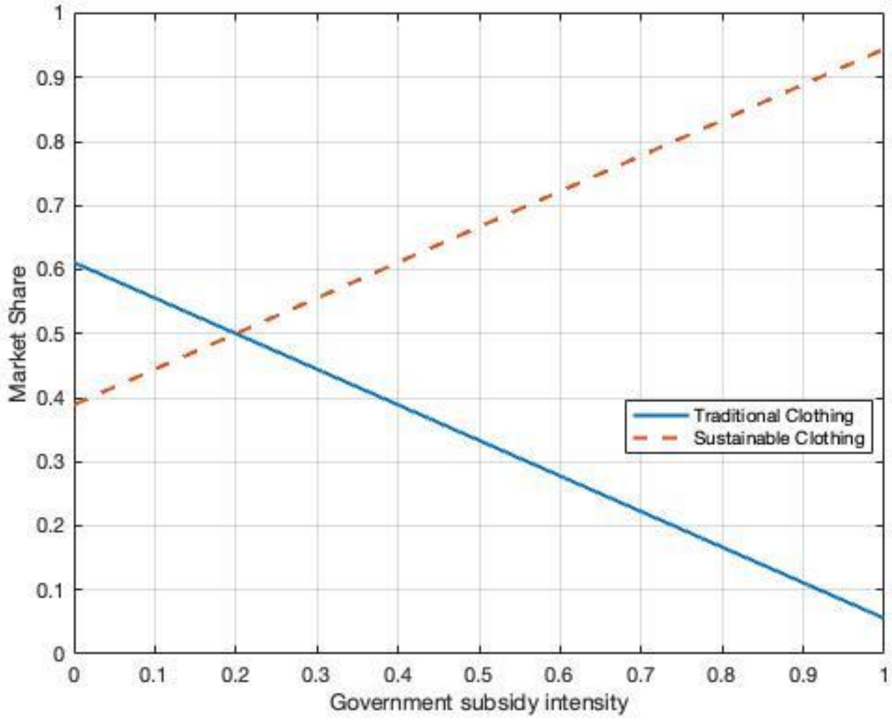


Fig 5.15: Impact of consumer-side government subsidies on market shares.

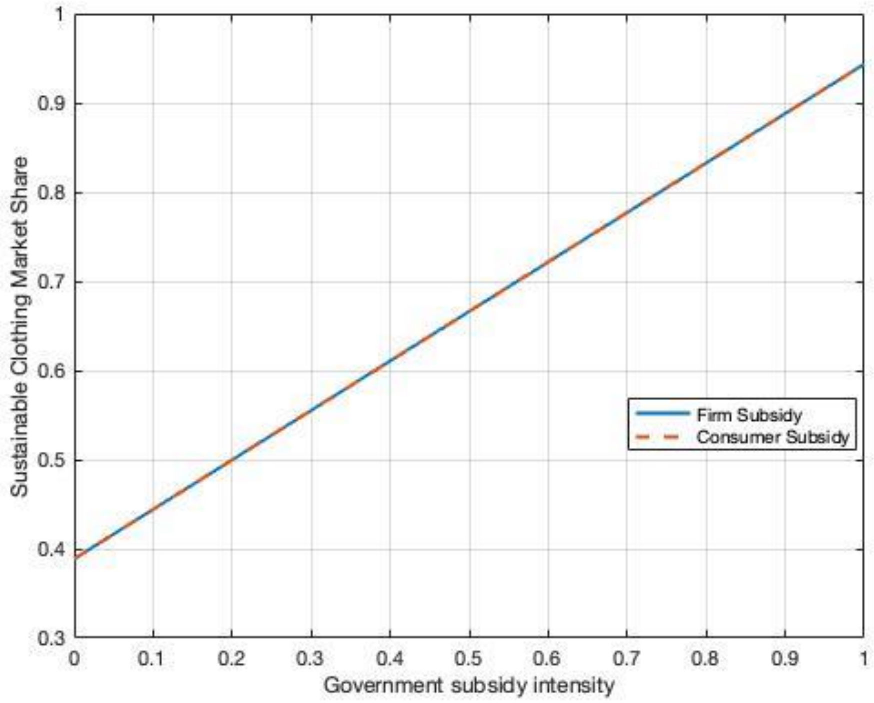


Fig 5.16: Comparison of market shares under two government subsidy schemes.

5.4.2.3. Impact of government subsidy intensity on firm profits

Fig 5.17 illustrates how the profits of traditional and sustainable apparel firms evolve with increasing subsidy intensity under the scenario in which the government subsidizes sustainable apparel enterprises. By directly reducing production costs, the government alleviates the cost burden on sustainable apparel firms and enhances their price competitiveness, leading to a steady increase in profits. Meanwhile, the market share of traditional apparel firms is progressively eroded by sustainable alternatives, weakening their relative competitiveness and resulting in a gradual decline in profits.

Fig 5.18 depicts how the profits of traditional and sustainable apparel firms change with increasing subsidy intensity when the government provides subsidies to consumers. The government stimulates the market from the demand side by enhancing consumers' purchasing power for sustainable products. Sustainable apparel firms can leverage the increased willingness to pay brought by subsidies to raise prices, thereby converting the subsidy effect more directly into profit growth. The market share of traditional apparel continues to shrink, and their profits decline steadily as subsidy intensity increases.

Fig 5.19 compares the profits of sustainable apparel firms under the two subsidy mechanisms. The two curves in the figure completely overlap, indicating that both subsidy approaches have an identical impact on firm profitability.

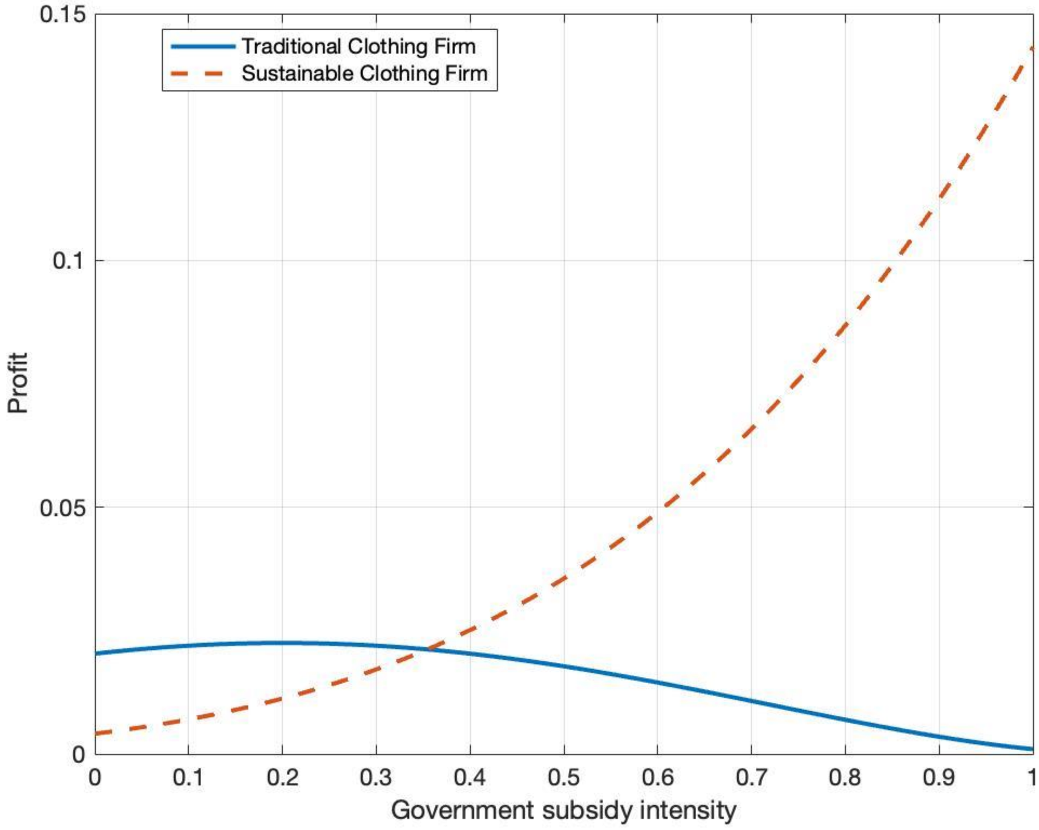


Fig 5.17: Impact of firm-side government subsidies on profits.

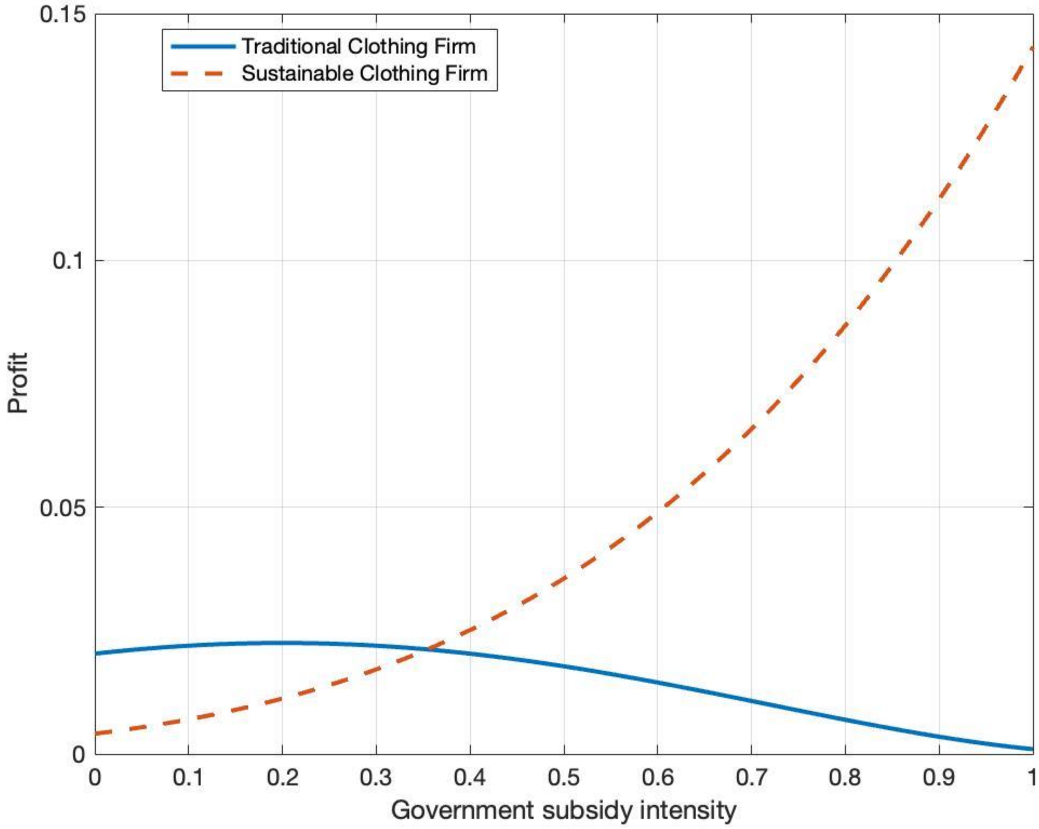


Fig 5.18: Impact of consumer-side government subsidies on profits.

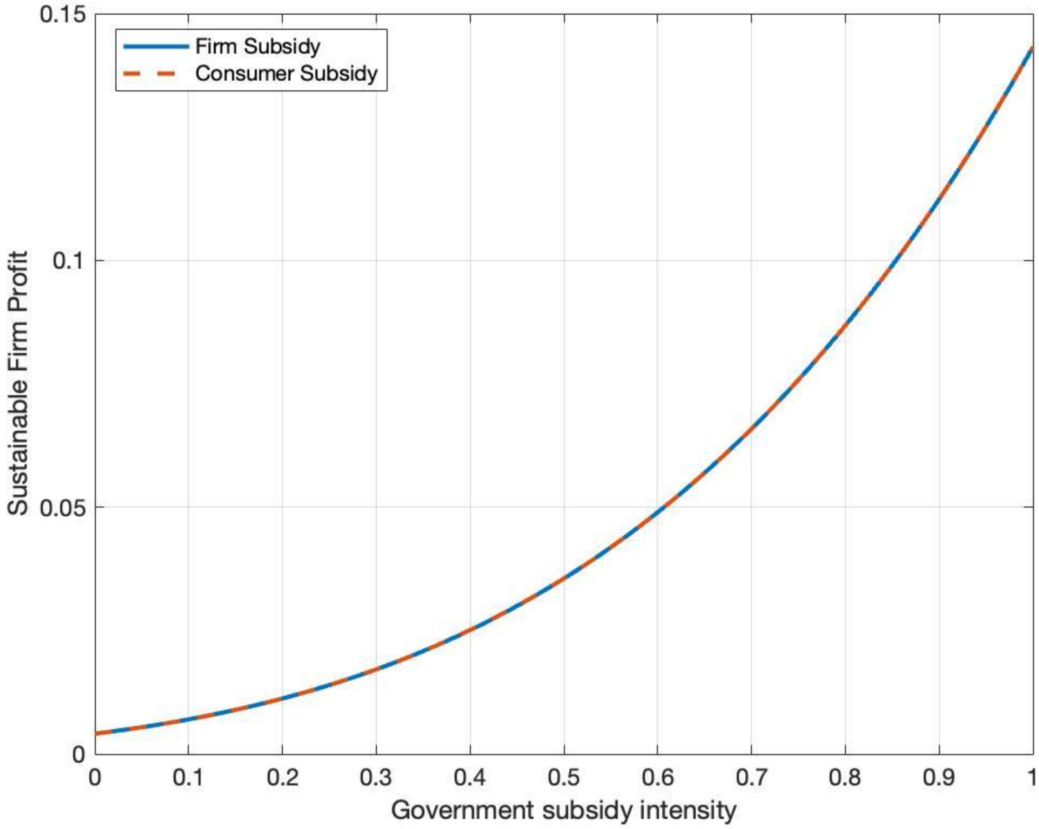


Fig 5.19: Comparison of profits under two government subsidy schemes.

5.5. Summary

This study investigates the impacts of consumer environmental awareness and government subsidies on the prices, market shares, profits, and social welfare associated with traditional and sustainable apparel. Finally, numerical simulations are conducted to derive the following research conclusions.

5.5.1. Key findings

In the absence of government subsidies, rising consumer environmental awareness significantly increases the prices of both traditional and sustainable apparel, as well as the premium between them, with the price increase being more pronounced for sustainable apparel. This phenomenon stems from differences in the pricing mechanisms of the two products. Increased environmental awareness enhances consumers' perceived utility of sustainable apparel, raising their willingness to pay and thus driving up its price. In contrast, the price increase of traditional apparel is mainly driven by the substitution effect, whereby rising prices of sustainable apparel pushing traditional apparel prices upward. In terms of market structure, the market share of traditional apparel is negatively correlated with consumer environmental awareness but positively correlated with the unit cost coefficient of sustainable apparel, whereas sustainable apparel exhibits the opposite trend. Increased environmental awareness positively affects firm profitability, contributing to simultaneous profit growth for both types of apparel firms. In contrast, as the unit cost coefficient of sustainable apparel increases, the profitability of both firms is compressed to varying degrees.

When the government subsidizes sustainable apparel firms, higher subsidies promote greater investment in sustainable technologies, thereby enhancing product sustainability.

●When $\gamma < \delta$, increasing subsidies lead to rising prices for both traditional and sustainable apparel.

●When $\gamma > \delta$, the prices of both apparel types decline.

Increasing subsidies further reduces the unit cost of sustainable apparel, expanding its market share. However, due to the substitution effect, the market share of traditional apparel declines. Higher government subsidies lead to greater profits for sustainable apparel firms. In contrast, the impact on traditional apparel profits varies: when traditional firms dominate the market, their profits are positively correlated with subsidy levels; however, when sustainable firms dominate, traditional firms' profits are negatively correlated with subsidies.

●When $\gamma < \delta$, increasing subsidies raise traditional apparel prices.

●When $\gamma > \delta$, higher subsidies result in a decline in traditional apparel prices.

Both types of subsidies do not alter product sustainability, market share, or firm profitability. However, direct consumer subsidies increase the price of sustainable apparel. This is because such subsidies enhance consumer utility, increasing their willingness to pay for sustainable apparel. In contrast, subsidies directed at firms reduce production costs, prompting firms to lower their prices.

5.5.2. Policy recommendations

These findings underscore the necessity for well-targeted policy interventions. Building on these insights, we propose the following policy recommendations:

Strengthen consumer environmental awareness to enhance its guiding role in the sustainable market. The government should intensify the promotion of sustainable consumption concepts by means such as environmental education, public campaigns, and eco-label certifications, in order to raise public awareness and acceptance of sustainable apparel and fully unlock the market potential of sustainable consumption.

Design enterprise subsidy policies with precision, tailoring measures to firm-specific conditions to improve policy efficiency. When implementing subsidies for firms, the government should thoroughly assess the current market structure and the firms' positions within it. Subsidy intensity should be dynamically adjusted according to market structure to prevent over-subsidization, which may lead to resource misallocation or market distortion.

Explore demand-side subsidy mechanisms to enhance consumers' willingness to pay for sustainable products. Compared to firm-level subsidies, consumer subsidies more directly increase purchase willingness, thereby driving up the price of sustainable apparel and strengthening its brand value. It is recommended that the government pilot policy instruments such as "green consumption vouchers" or "sustainable product purchase subsidies," with a focus on supporting green consumption choices among low- and middle-income groups. At the same time, a robust qualification review and regulatory mechanism should be established to ensure accurate subsidy targeting and prevent fund misuse.

Integrate the differences in subsidy pathways to design coordinated policies across the supply and demand sides. Although the two subsidy mechanisms follow different pathways, they exhibit equivalent effectiveness in improving market share and firm profitability. Enterprise subsidies focus on reducing supply-side costs, while consumer subsidies stimulate demand by enhancing purchasing power. Therefore, it is recommended that the government adopt a "supply-demand coordinated" hybrid subsidy strategy in implementation, flexibly combining both approaches based on market stage, to simultaneously stimulate green innovation by firms and expand the consumer base for sustainable products.

6. Regulating pseudo-sustainability in platform-based apparel markets: Evolutionary dynamics and governance strategies

6.1. Introduction

Sustainable apparel, due to its inherent characteristics of information asymmetry and low observability, provides fertile ground for enterprises to engage in "pseudo-sustainable production." Some apparel manufacturers exploit this by producing low-cost apparel that is falsely marketed as sustainable in order to capture sustainability premiums (Morozova, 2024; McNeill et al., 2025). According to a joint investigation conducted by the UK Competition and Markets Authority and the Netherlands Authority for Consumers and Markets, 40% of 500 global e-commerce platforms in the apparel, cosmetics, and food sectors were found to be involved in misleading sustainability claims (Wang et al., 2025). Such behaviors not only damage the credibility of e-commerce platforms but also pose systemic threats to the sustainable economic system as a whole (Chen and Dagestani, 2023; Santos and Marques, 2023; Free et al., 2024). Therefore, enhancing platform-level regulations and standardizing the sustainable apparel sector has become an urgent issue for academics.

There exists a typical principal-agent relationship between platforms and apparel producers. As service providers, platforms assist producers in expanding their market share by offering distribution channels, logistics, payment processing, and promotional support (Xu et al., 2025; Zhang et al., 2025) , while earning transaction commissions and advertising fees. Concurrently, platforms are tasked with compliance enforcement, credit evaluation, and customer service responsibilities, including scheduled and unscheduled product quality inspections, dynamic credit scoring systems, and financial penalties for rule violations (Sheng and Ni, 2024; Leng et al., 2025). These services cover regulatory costs but also generate revenue through membership subscriptions and value-added services. Together, these investments and diversified revenue sources constitute the cost-revenue structure of the platform.

Given the symbiotic nature of the relationship between platforms and apparel producers, relying solely on ex-ante regulatory mechanisms implemented by the platform is often insufficient to curb pseudo-sustainable production behaviors (Wu et al., 2020; Wang, 2023). In this context, consumer whistleblowing mechanisms serve as a critical supplement. by fostering collaboration between platforms and consumers, such mechanisms leverage reputational incentives to encourage apparel companies to standardise their production practices (Li et al., 2023; Yue et al., 2024). Second, when pseudo-sustainable practices are exposed and trigger negative evaluations, the platform initiates punitive measures based on reputational safeguarding (Bin et al., 2020; Xiao, 2022). Finally, consumers weigh their participation based on the time cost of whistleblowing and the anticipated economic return, with moderate financial incentives proving effective in enhancing their willingness to participate (Fargetta and Scrimali, 2025). This multi-stakeholder regulatory approach has emerged as a significant institutional innovation in the governance of sustainable production.

A substantial literature has investigated the influence of mechanisms of sustainability labels. Michaud et al., (2013) demonstrated empirically that consumers exhibit significantly greater purchase intention for products bearing sustainability labels compared to those without. Chekima et al., (2016) further argued that this price premium is, in essence, compensation for information asymmetry. Unlike manufacturer-initiated or government-/third-party-certified labels, platform-issued sustainability labels are often created and administered by the platforms themselves. Relying on their expansive data infrastructure and supply chain management capabilities, platforms comprehensively assess and rate the sustainability levels of products (Liu et al., 2025; Yao et al., 2025). Guo et al., (2020) developed a supply chain game-theoretical model to demonstrate how sustainability labels can optimize both retail and agency models. Torma et al., (2021) highlighted the regulatory and trust challenges that arise from information asymmetry, high compliance costs, and manufacturers' pseudo-sustainable behaviors. Kumar et al., (2021) found that the grading level of sustainability labels significantly influences consumers’ brand evaluations of sustainable products.

While existing research has yielded valuable findings, several important limitations remain:

(1) Previous studies have acknowledged the negative impact of pseudo-sustainability labels on consumer trust but have not examined

the dynamic evolution of stakeholder strategies, particularly the lack of quantitative analysis on strategic interaction and evolutionary pathways. This static perspective is inadequate for explaining the formation of market equilibrium.

(2) Although the development of the platform economy has introduced new regulatory challenges, there is a lack of systematic investigation into the dual-role tension of platforms in the governance of sustainability labels—as both standard-setters seeking commercial interests and regulators responsible for ecological integrity.

(3) Despite recognition of the complementary regulatory role of consumer whistleblowing, most studies have overlooked how consumers' concern for sustainable apparel, their reporting costs, and the presence of reputation-based incentives influence their decision-making behavior.

To address these research gaps, this study offers the following marginal contributions:

(1) A tripartite evolutionary game model involving consumers, apparel manufacturers, and platforms is constructed to reveal the dynamic evolutionary pathways and stability conditions among key stakeholders. By applying evolutionary game theory, the model quantitatively simulates strategic interactions under varying conditions, such as production costs, reporting costs and benefits, and reputation-based reward-punishment mechanisms. Through analysis of evolutionary stable strategies and trajectories, the study uncovers the underlying mechanisms of market equilibrium formation and identifies

the key conditions and internal logic for sustainable development in the apparel supply chain.

(2) This study focuses on the dual roles played by platforms in both the creation and enforcement of sustainability labels. It systematically deconstructs platform behavior and incentive structures, examining how the conflict between profit maximization and ecological credibility shapes market governance. The analysis reveals potential moral hazard scenarios under varying market conditions and proposes strategies for optimizing platform governance.

(3) The role of consumer whistleblowing is integrated into the analytical framework to explore its functional mechanism and incentive design in platform governance. By employing the evolutionary game model, the study assesses the impact of consumer reporting on platform and enterprise strategies, explores the collaborative governance potential of post hoc regulation, and identifies the constraints that must be addressed to effectively incentivize consumer participation in sustainability oversight.

6.2. Model construction and assumptions

6.2.1. Model assumptions

Assumption 1: The strategy set available to apparel manufacturer i is defined as {producing sustainable apparel, producing pseudo-sustainable apparel}. Producing sustainable apparel implies that the manufacturer adheres strictly to pre-defined sustainability requirements throughout the processes of production, management, or distribution.

In contrast, producing pseudo-sustainable apparel refers to deceptive practices whereby the manufacturer aims to reduce costs and increase profits by only superficially complying with sustainability requirements. The corresponding probabilities for choosing these strategies are $\{x, 1-x\}$, where $0 \leq x \leq 1$. The cost of producing sustainable apparel is denoted as C_1, while the cost of producing pseudo-sustainable apparel is C_2, with $C_1 > C_2$. The revenue generated by both types of apparel is assumed to be R_0.

Assumption 2: The strategy set for consumer j is{sustainability-concerned, not sustainability-concerned}. Sustainability-concerned consumers are defined as environmentally conscious individuals who actively search for and are capable of identifying sustainability-related information and will preferentially purchase sustainable apparel. Furthermore, if such consumers discover that the purchased item is pseudo-sustainable, they will report it to the platform. A higher degree of concern corresponds to a higher sensitivity parameter λ. Non-concerned consumers, on the other hand, are neither sensitive to nor interested in sustainability information and cannot distinguish between genuine and pseudo-sustainable products. The probabilities of these two consumer types are $\{y, 1-y\}$,with $0 \leq y \leq 1$. It is assumed that non-concerned consumers derive utility U from purchasing either sustainable or pseudo-sustainable apparel. Sustainability-concerned consumers derive utility $(1+\lambda)U$, from purchasing sustainable apparel and utility $(1-\lambda)U$ from purchasing pseudo-sustainable apparel.

Assumption 3: The strategy set for platform k is defined as {strict regulation, lenient regulation}. Strict regulation refers to the platform's practice of conducting regular inspections of sustainable apparel in accordance with relevant standards and actively responding to consumer feedback. *Lenient regulation* implies selective inspections and passive response to consumer complaints. The respective probabilities for these strategies are$\{z, 1-z\}$, with $0 \leq z \leq 1$. If the platform adopts a strict regulatory strategy, it gains revenue of $R_1$and incurs a regulatory cost of C_3. Under lenient regulation, the platform gains revenue R_2 and incurs a lower regulatory cost C_4, where $C_3 > C_4$. Penalties imposed on pseudo-sustainable producers include: P_1 :penalties resulting from platform inspections, P_2 : penalties resulting from consumer reports. Under strict and lenient regulation, the probability that the platform inspects sustainable apparel are Q_1 and Q_2 , respectively, where$Q_1 > Q_2 > 0$. As a result, firms producing pseudo-sustainable apparel suffer economic losses of Q_1P_1 or Q_2P_1, depending on the platform's regulatory strategy. In addition, strict regulation enhances the platform's reputation, yielding an additional benefit of I_1, whereas lenient regulation harms platform reputation, leading to a loss of I_2.

Assumption 4: If a consumer identifies pseudo-sustainable apparel and reports it to the platform, the consumer receives a reward of R from the platform but must incur a time cost of C_5. When a consumer purchases sustainable apparel, it enhances the brand reputation of the producing firm among consumers, generating a benefit

I_3. Conversely, if a pseudo-sustainable product is purchased, it triggers negative word-of-mouth and causes a reputational loss denoted as I_4.

The relevant parameters are presented in Table 6.1, and the research framework of this study is illustrated in Fig. 6.1.

Table 6.1.

Description of model parameters

Symbol	Description
R	Reward received by consumers for reporting pseudo-sustainable apparel to the platform
R_0	Revenue obtained by apparel firms from producing sustainable/pseudo-sustainable apparel
R_1/R_2	Platform revenue under strict/lenient regulatory strategies
C_1/C_2	Production cost of sustainable/pseudo-sustainable apparel for manufacturers
C_3/C_4	Regulatory cost incurred by the platform under strict/lenient supervision
C_5	Time cost borne by consumers for reporting to the platform
U	Baseline utility, i.e., the utility obtained by non-concerned consumers from any apparel purchase
λ	Degree of consumer concern for sustainable apparel
I_1/I_2	Platform's reputational gain/loss under strict/lenient regulation
I_3/I_4	Reputational gain/loss for apparel firms from producing sustainable/pseudo-sustainable apparel
Q_1/Q_2	Probability of platform inspections under strict/lenient regulation
P_1	Economic penalty imposed by the platform after detecting pseudo-sustainable production through inspections
P_2	Economic penalty imposed by the platform based on consumer reports of pseudo-sustainable production

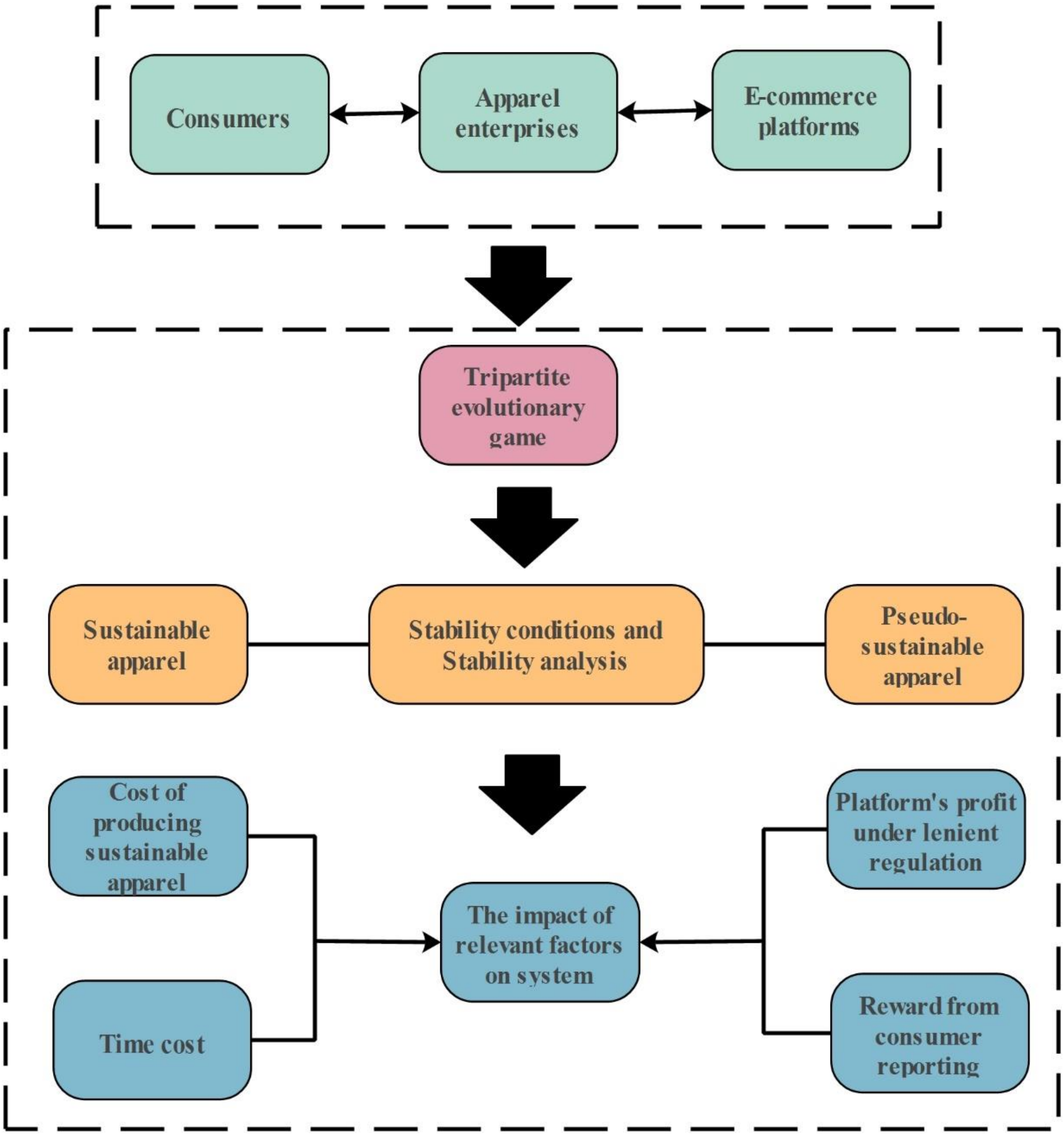


Fig. 6.1. research framework

6.2.2. Model computation and stability analysis of equilibrium points

Based on the assumptions outlined above and the strategic interactions among consumers, sustainable apparel manufacturers, and e-commerce platforms, the tripartite game can be formalized through a payoff matrix as shown in Table 6.2.

Table 6.2.

Payoff matrix of the tripartite evolutionary game

Strategy	Manufacturer payoff	Consumer payoff	Platform payoff
(0,0,0)	$R_0 - C_2 - I_4 - Q_2P_1$	$U - R_0$	$R_2 - C_4 - I_2 + Q_2P_1$
(1,0,0)	$R_0 - C_1 + I_3$	$U - R_0$	$R_2 - C_4 - I_2$
(0,0,1)	$R_0 - C_2 - I_4 - Q_1P_1$	$U - R_0$	$R_1 - C_3 + I_1 + Q_1P_1$
(1,0,1)	$R_0 - C_1 + I_3$	$U - R_0$	$R_1 - C_3 + I_1$
(0,1,0)	$R_0 - C_2 - I_4 - Q_2P_1 - P_2$	$(1-\lambda)U - R_0 +$ $R - C_5$	$R_2 - C_4 - I_2 +$ $Q_2P_1 + P_2 - R$
(1,1,0)	$R_0 - C_1 + I_3$	$(1+\lambda)U - R_0$	$R_2 - C_4 - I_2$
(0,1,1)	$R_0 - C_2 - I_4 - Q_1P_1 - P_2$	$(1-\lambda)U - R_0 +$ $R - C_5$	$R_1 - C_3 + I_1 +$ $Q_1P_1 + P_2 - R$
(1,1,1)	$R_0 - C_1 + I_3$	$(1+\lambda)U - R_0$	$R_1 - C_3 + I_1$

Based on the payoff matrix in Table 6.2, the expected payoffs for apparel manufacturers choosing different strategies can be derived as follows: The expected payoff of producing sustainable apparel, denoted as E_{11}, The expected payoff of producing pseudo-sustainable apparel, denoted as E_{12} , The average expected payoff for the apparel manufacturer, denoted as E_1 :

$$\begin{aligned} E_{11} &= (1-y)(1-z)(R_0 - C_1 + I_3) + (1-y)z(R_0 - C_1 + I_3) \\ &\quad + y(1-z)(R_0 - C_1 + I_3) + yz(R_0 - C_1 + I_3) \\ &= R_0 - C_1 + I_3 \end{aligned} \tag{6.1}$$

$$E_{12} = (1-y)(1-z)(R_0 - C_2 - I_4 - Q_2P_1) + y(1-z)(R_0 - C_2 - I_4 - Q_1P_1) + y(1-z)(R_0 - C_2 - I_4 - Q_2P_1 - P_2) + yz(R_0 - C_2 - I_4 - Q_1P_1 - P_2)$$

$$\begin{aligned} &= (R_0 - C_2 - I_4 - Q_1P_1 - P_2)y + (C_2 + I_4 + Q_2P_1 - R_0)z \\ &\quad + (R_0 - C_2 - I_4 - Q_2P_1) \end{aligned}$$

(6.2)

$$E_1 = xE_{11} + (1-x)E_{12} \tag{6.3}$$

The corresponding replicator dynamic equation for the manufacturer strategy is:

$$F(x) = \frac{dx}{dt} = x(E_{11} - E_1)$$
$$= x(1-x)\begin{bmatrix} (C_2 - C_1 + I_3 + I_4 + Q_2P_1) - (R_0 - C_2 - I_4 - Q_1P_1 - P_2)y \\ -(C_2 + I_4 + Q_2P_1 - R_0)z \end{bmatrix}$$

(6.4)

Similarly, the expected payoff for sustainability-concerned consumers, denoted as E_{21}.The expected payoff for non-concerned consumers, denoted as E_{22}.The average expected payoff for consumers, denoted as E_2 :

$$\begin{aligned} E_{21} = {} & (1-x)(1-z)\big((1-\lambda)U - R_0 + R - C_5\big) \\ & + x(1-z)\big((1+\lambda)U - R_0\big) \\ & + (1-x)z\big((1-\lambda)U - R_0 + R - C_5\big) \\ & + xz\big((1+\lambda)U - R_0\big) \\ = {} & \big((1-\lambda)U + R - C_5 - R_0\big) + (2\lambda U - R + C_5)x \end{aligned} \tag{6.5}$$

$$\begin{aligned} E_{22} = {} & (1-x)(1-z)(U - R_0) + x(1-z)(U - R_0) \\ & + (1-x)z(U - R_0) + xz(U - R_0) = U - R_0 \\ & = U - R_0 \end{aligned} \tag{6.6}$$

$$E_2 = yE_{21} + (1-y)E_{22} \tag{6.7}$$

The corresponding replicator dynamic equation for the consumer strategy is:

$$F(y) = \frac{dy}{dt} = y(E_{21} - E_2)$$

$$= y(1-y)[(-\lambda U + R - C_5) + (2\lambda U - R + C_5)x] \tag{6.8}$$

Next, the expected payoff for platforms adopting strict regulations, denoted as E_{31}. The expected payoff for platforms adopting lenient regulations, denoted as E_{32}. The average expected payoff for the platform, denoted as E_3 :

$$\begin{aligned} E_{31} = (1-x)(1-y)(R_1 - C_3 + I_1 + Q_1P_1) \\ + x(1-y)(R_1 - C_3 + I_1) \\ + (1-x)y(R_1 - C_3 + I_1 + Q_1P_1 + P_2 - R) \\ + xy(R_1 - C_3 + I_1) \end{aligned}$$

$$= (R_1 - C_3 + I_1 + Q_1P_1) - Q_1P_1x + (P_2 - R)y + (R - P_2)xy \tag{6.9}$$

$$\begin{aligned} E_{32} = (1-x)(1-y)(R_2 - C_4 - I_2 + Q_2P_1) \\ + x(1-y)(R_2 - C_4 - I_2) \\ + (1-x)y(R_2 - C_4 - I_2 + Q_2P_1 + P_2 - R) \\ + xy(R_2 - C_4 - I_2) \end{aligned}$$

$$= (R_2 - C_4 - I_2 + Q_2P_1) - Q_2P_1x + (P_2 - R)y + (R - P_2)xy \tag{6.10}$$

$$E_3 = zE_{31} + (1-z)E_{32} \tag{6.11}$$

The corresponding replicator dynamic equation for the platform strategy is:

$$F(z) = \frac{dz}{dt} = z(E_{31} - E_3)$$

$$= z(1-z)[(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) + (Q_1 - Q_2)P_1 - (Q_1 - Q_2)P_1x] \tag{6.12}$$

Finally, combining the three replicator dynamics equations from Equations (6.4), (6.8), and (6.12), the tripartite replicator dynamic system is given by:

$$\begin{cases} F(x) = x(1-x)\begin{bmatrix}\left(C_2 - C_1 + I_3 + I_4 + Q_2P_1\right) - \left(R_0 - C_2 - I_4 - Q_1P_1 - P_2\right)y \\ -\left(C_2 + I_4 + Q_2P_1 - R_0\right)z\end{bmatrix} \\ F(y) = y(1-y)[(-\lambda U + R - C_5) + (2\lambda U - R + C_5)x] \\ F(z) = z(1-z)\left[(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) + \left(Q_1 - Q_2\right)P_1 - \left(Q_1 - Q_2\right)P_1 x\right] \end{cases}$$

(6.13)

Setting each replicator equation in (6.13) to zero, $F(x)=F(y)=F(z)$ =0, yields eight equilibrium points in the three-dimensional strategy space $D = \{(x,y,z) | 0 \le x \le 1,\ 0 \le y \le 1, 0 \le z \le 1\}$, namely: $W_1(0,0,0)$, $W_2(1,0,0)$, $W_3(0,0,1)$, $W_4(1,0,1)$, $W_5(0,1,0)$, $W_6(1,1,0)$, $W_7(0,1,1)$ and $W_8(1,1,1)$. These represent the pure-strategy equilibrium states of the evolutionary game system.

$$令M = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix}$$

$$= \begin{bmatrix} \begin{pmatrix} (C_2 - C_1 + I_3 + I_4 + Q_2P_1) - (R_0 - C_2 - I_4 - Q_1P_1 - P_2)y \\ -(C_2 + I_4 + Q_2P_1 - R_0)z \end{pmatrix}(1-2x) & (C_2 + I_4 + Q_1P_1 + P_2 - R_0)x(1-x) & (R_0 - C_2 - I_4 - Q_2P_1)x(1-x) \\ (2\lambda U - R + C_5)y(1-y) & [-\lambda U + R - C_5 + (2\lambda U - R + C_5)x](1-2y) & 0 \\ -(Q_1 - Q_2)P_1 z(1-z) & 0 & (1-2z)[(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) + (Q_1 - Q_2)P_1(1-x)] \end{bmatrix}$$

(6.14)

According to Lyapunov stability theory, if all eigenvalues β of the Jacobian matrix at a given point are negative, the evolutionary game system is considered asymptotically stable at that equilibrium. If the eigenvalues include both positive and negative values, the point is classified as a saddle point, indicating local instability in certain directions. Conversely, if all eigenvalues are positive, the system is deemed unstable at that equilibrium (Parks, 1992; Gao et al., 2023).

Table 6.3.

System equilibrium point eigenvalues and stability analysis

Equilibrium point	Eigenvalue			Stability condition
	β_{i1}	β_{i2}	β_{i3}	
$W_1(0,0,0)$	$C_2 - C_1 + I_3 + I_4 + Q_2P_1$	$-\lambda U + R - C_5$	$(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) + (Q_1 - Q_2)P_1$	ESS
W_2 (1,0,0)	$C_1 - C_2 - I_3 - I_4 - Q_2P_1$	λU	$R_1 - R_2 + C_4 - C_3 + I_1 + I_2$	Saddle point
W_3 (0,0,1)	$R_0 - C_1 + I_3$	$-\lambda U + R - C_5$	$-(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) - (Q_1 - Q_2)P_1$	ESS
W_4 (1,0,1)	$C_1 - R_0 - I_3$	λU	$-(R_1 - R_2 + C_4 - C_3 + I_1 + I_2)$	Saddle point
W_5 (0,1,0)	$2C_2 - C_1 - R_0 + I_3 + 2I_4 + Q_2P_1 + Q_1P_1 + P_2$	$\lambda U - R + C_5$	$R_1 - R_2 + C_4 - C_3 + I_1 + I_2 + (Q_1 - Q_2)P_1$	ESS
W_6 (1,1,0)	$-(2C_2 - C_1 - R_0 + I_3 + 2I_4 + Q_2P_1 + Q_1P_1 + P_2)$	$-\lambda U$	$R_1 - R_2 + C_4 - C_3 + I_1 + I_2$	ESS
W_7 (0,1,1)	$C_2 - C_1 + I_3 + I_4 + Q_1P_1 + P_2$	$\lambda U - R + C_5$	$-(R_1 - R_2 + C_4 - C_3 + I_1 + I_2) - (Q_1 - Q_2)P_1$	ESS
W_8 (1,1,1)	$-(C_2 - C_1 + I_3 + I_4 + Q_1P_1 + P_2)$	$-\lambda U$	$-(R_1 - R_2 + C_4 - C_3 + I_1 + I_2)$	ESS

As shown in Table 6.3, the eigenvalues corresponding to equilibrium points W_2 (1,0,0) and W_4 (1,0,1) are greater than zero. Therefore, these points are unstable equilibria and will not be discussed further. The following analysis will focus on the remaining six scenarios: W_1(0,0,0),W_3 (0,0,1),W_5 (0,1,0),W_6 (1,1,0), W_7 (0,1,1) and W_8 (1,1,1).

6.3. Results and discussion

6.3.1. Verification of equilibrium point stability conditions

Numerical simulations are conducted using MATLAB R2021b to investigate the evolutionary paths of strategic behaviors for apparel manufacturers, consumers, and e-commerce platforms. These simulations are aimed at verifying the stability conditions of the six equilibrium points: W_1(0,0,0), W_3 (0,0,1), W_5 (0,1,0), W_6 (1,1,0), W_7

(0,1,1) and W_8 (1,1,1). Based on the aforementioned research hypotheses and the eigenvalue calculation results presented in Table 6.3, the parameter values of each equilibrium point are set as shown in Table 6.4, upon which numerical simulations are conducted.

Table. 6.4.

Equilibrium Point and Parameter Value

Parameter	Equilibrium Point					
	W_1(0,0,0)	W_3 (0,0,1)	W_5 (0,1,0)	W_6 (1,1,0)	W_7 (0,1,1)	W_8 (1,1,1)
R	20	20	30	30	30	30
R_0	90	90	90	80	90	80
R_1/R_2	60/75	90/60	60/75	60/75	90/60	90/60
C_1/C_2	120/80	120/80	120/80	120/110	120/80	120/110
C_3/C_4	30/10	30/10	30/10	30/10	30/10	30/10
C_5	10	10	5	5	5	5
U	50	50	50	50	50	50
λ	0.3	0.3	0.3	0.3	0.3	0.3
I_1/I_2	15/-6	15/-6	15/-6	15/-6	15/-6	15/-6
I_3/I_4	5/10	5/10	5/10	5/10	5/10	5/10
Q_1/Q_2	0.8/0.3	0.8/0.3	0.8/0.3	0.8/0.3	0.8/0.3	0.8/0.3
P_1/P_2	10/8	10/8	10/8	10/8	10/8	10/8

6.3.1.1. Verification of stability conditions for W_1(0,0,0)

As shown in Table 6.4, the parameter values for W_1(0,0,0) satisfy the conditions listed in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms can be set respectively as (0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8). Based on these values, simulation analyses of their behavioral strategies under different initial willingness conditions are conducted. As illustrated in Fig. 6.2, despite the variations in initial willingness, the strategies of the three actors ultimately evolve toward the same outcome: {producing pseudo-sustainable apparel, sustainability indifference, and loose supervision}. This indicates that initial willingness does not affect the final behavioral strategy choices of the three actors; however, it does influence the time required to reach equilibrium. Lower initial willingness leads to a shorter time to reach equilibrium compared to higher initial willingness.

Under the $W_1(0,0,0)$ scenario, the condition $C_1 > C_2 + I_3 + I_4 + Q_2P_1$ holds, indicating that the cost for apparel manufacturers to produce sustainable apparel exceeds the cost of producing pseudo-sustainable apparel, the reputation rewards for sustainable production, the reputation losses from pseudo-sustainable production, and the penalties imposed by the government. The condition $C_5 > -\lambda U + R$ implies that the time cost for consumers to report to the platform exceeds the sum of their utility loss and the reward for reporting pseudo-sustainable apparel. Additionally, $C_3 + R_2 > R_1 + C_4 + I_1 + I_2 + (Q_1 - Q_2)P_1$ suggests that the total regulatory cost for the platform under strict supervision and the profits under loose supervision are greater than the platform's gains from strict supervision, its regulatory cost under loose supervision, the reputation rewards under strict supervision, the reputation losses under loose supervision, and the difference in penalties between strict and loose supervision. Ultimately, apparel manufacturers choose to produce pseudo-sustainable apparel, consumers adopt a sustainability-indifferent strategy, and the e-commerce platform opts for loose supervision.

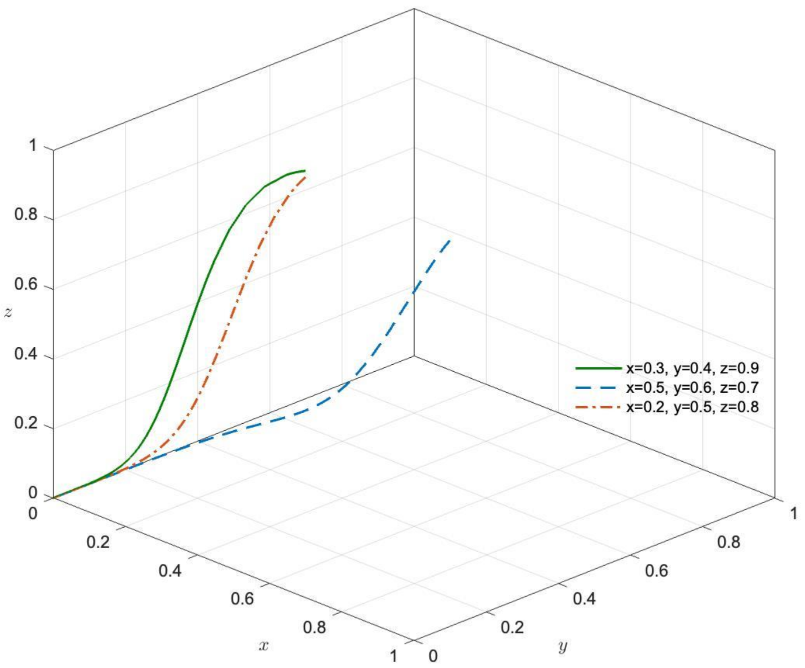


Fig. 6.2 Verification of stability conditions for W_1(0,0,0).

6.3.1.2. Verification of stability conditions for W_3(0,0,1)

In Table 6.4, the parameter values for W_3 (0,0,1) satisfy the conditions outlined in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms are set as (0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8) respectively. Simulation analyses are then conducted on the behavioral strategies of the three parties under different initial willingness scenarios. As illustrated in Fig. 6.3, despite variations in initial willingness, the strategies of the three actors ultimately evolve toward W3(0,0,1), namely: {producing pseudo-sustainable apparel, sustainability indifference, and strict supervision}. This indicates that initial willingness does not affect the final strategic choices of the three actors, but it does influence the time required to reach equilibrium. As the system approaches 0, lower initial willingness leads to a shorter time to reach equilibrium compared to higher initial willingness; conversely, as the system approaches 1, lower initial willingness results in a longer time to reach equilibrium.

Under the $W_3(0,0,1)$ scenario, the condition $C_1 > R_0 + I_3$ holds, indicating that the cost for apparel manufacturers to produce sustainable apparel exceeds the combined benefits and reputation rewards associated with sustainable production. The condition $C_5 > -\lambda U + R$ implies that the time cost for consumers to report to the platform exceeds the sum of the utility loss and the reward for reporting pseudo-sustainable apparel. Moreover, the condition $I_1 - C_3 + (Q_1 - Q_2)P_1 > R_2 - (R_1 + C_4 + I_2)$ suggests that the total of the platform's reputation rewards for strict supervision, the difference in penalties between strict and loose supervision, and the regulatory cost under strict supervision is greater than the net gains from loose and strict supervision, the regulatory cost under loose supervision, and the reputation loss under loose supervision. Ultimately, apparel manufacturers choose to produce pseudo-sustainable apparel, consumers adopt a sustainability-indifferent strategy, and the e-commerce platform opts for strict supervision.

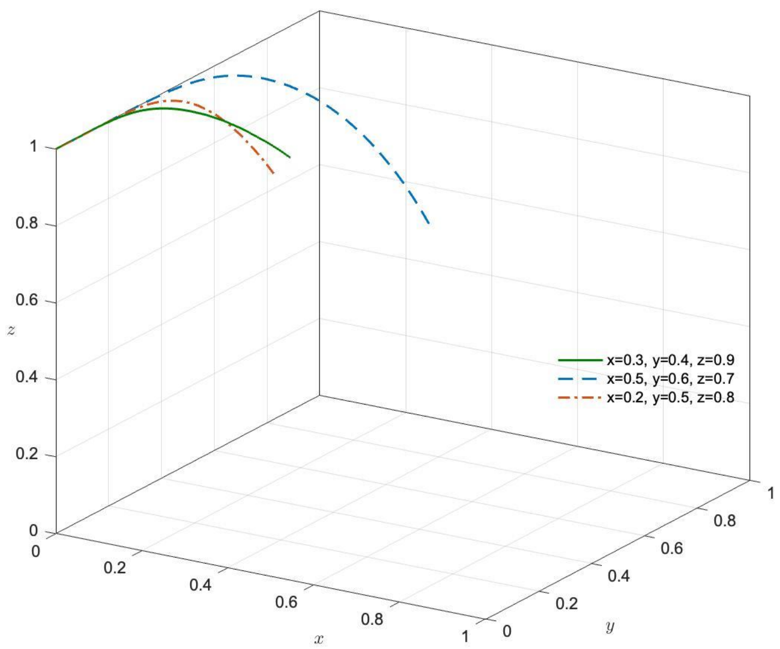


Fig. 6.3 Verification of stability conditions for W_3(0,0,1)

6.3.1.3. Verification of stability conditions for W_5(0,1,0)

In Table 6.4, the parameter values for W_5 (0,1,0) satisfy the conditions listed in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms are set as (0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8), respectively. Simulation analyses are then conducted to examine the behavioral strategies of the three parties under different initial willingness scenarios. As shown in Fig. 6.4, regardless of differences in initial willingness, the strategies of the three actors ultimately evolve toward W_5 (0,1,0), namely: {producing pseudo-sustainable apparel, sustainability concern, and loose supervision}. This demonstrates that while initial willingness does not influence the final strategic choices of the actors, it can affect the time needed to reach equilibrium.

Under the $W_5(0,1,0)$ scenario, the condition $C_1 + R_0 > 2C_2 + I_3 + 2I_4 + (Q_1 + Q_2)P_1 + P_2$ indicates that the total cost and benefits of producing sustainable apparel are greater than the combined benefits of producing pseudo-sustainable apparel, the reputation rewards for sustainable production, the reputation losses from pseudo-sustainable production, and the regulatory penalties resulting from both platform inspections and consumer reports. The condition $R > \lambda U + C_5$ implies that the reward consumers receive for reporting pseudo-sustainable apparel exceeds the combined time cost of reporting and the increase in consumer utility. Furthermore, $R_2 > R_1 + (C_4 - C_3) + I_1 + I_2 + (Q_1 - Q_2)P_1$ means that the platform's profit from loose supervision exceeds the difference in regulatory costs between loose and strict supervision, the reputation rewards from strict supervision, the reputation losses from loose supervision, and the difference in penalties between the two regulatory modes. Ultimately, apparel manufacturers opt to produce pseudo-sustainable apparel, consumers adopt a sustainability-concerned strategy, and the e-commerce platform chooses loose supervision.

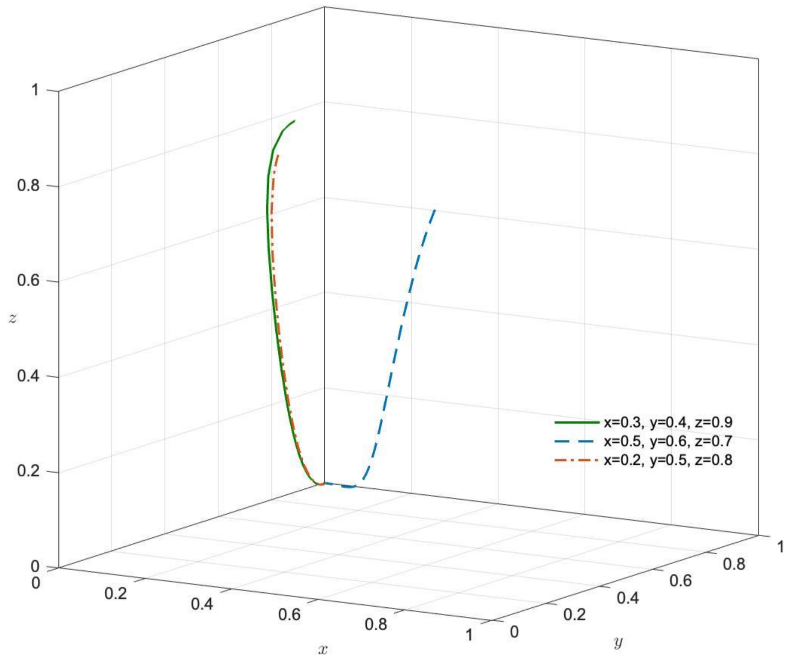


Fig. 6.4 Verification of stability conditions for W_5(0,1,0)

6.3.1.4. Verification of stability conditions for W_6(1,1,0)

In Table 6.4, the parameter values for W_6 (1,1,0) satisfy the conditions outlined in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms are set as (0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8), respectively. Simulation analyses are then conducted to examine the behavioral strategies of the three parties under different initial willingness scenarios. As shown in Fig. 6.5, despite variations in initial willingness, the strategies of the three actors ultimately evolve toward W_6(1,1,0).

Under the W_6 (1,1,0) scenario, the condition $C_1 < 2C_2 + I_3 + 2I_4 + (Q_1 + Q_2)P_1 + P_2 - R_0$ indicates that the cost for apparel manufacturers to produce sustainable apparel is less than the combined benefits of producing pseudo-sustainable apparel, the reputation rewards for sustainable production, the reputation losses from pseudo-sustainable production, the regulatory penalties from both platform inspections and consumer reports, and the net revenue difference from production. The condition $\lambda U > 0$ means that the increase in consumer utility is positive. Furthermore, the condition $R_2 > R_1 + (C_4 - C_3) + I_1 + I_2$ suggests that the platform's profit under loose supervision exceeds the gains from strict supervision, the difference in regulatory costs between strict and loose supervision, the reputation rewards under strict supervision, and the reputation losses from loose supervision. Ultimately, apparel manufacturers choose to produce sustainable apparel, consumers adopt a sustainability-concerned strategy, and the e-commerce platform opts for loose supervision.

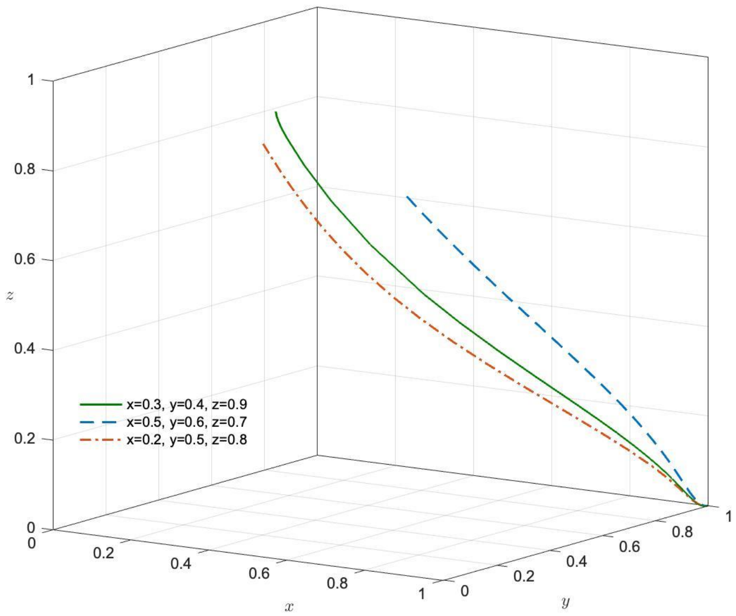


Fig. 6.5 Verification of stability conditions for $W_6(1,1,0)$

6.3.1.5. Verification of stability conditions for $W_7(0,1,1)$

In Table 6.4, the parameter values for $W_7(0,1,1)$ satisfy the conditions outlined in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms are set as

(0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8), respectively. Simulation analyses are conducted to examine the behavioral strategies of the three parties under different initial willingness scenarios. As shown in Fig. 6.6, regardless of the variations in initial willingness, the behavioral strategies of the three actors ultimately evolve toward $W_7(0,1,1)$.

Under the $W_7(0,1,1)$ scenario, the condition $C_1 > C_2 + I_3 + I_4 + Q_1P_1 + P_2$ indicates that the cost of producing sustainable apparel for manufacturers is greater than the combined cost of producing pseudo-sustainable apparel, the reputation rewards for sustainable production, the reputation losses from pseudo-sustainable production, and the regulatory penalties imposed through platform inspections and consumer reports. The condition $R > \lambda U + C_5$ suggests that the reward consumers receive for reporting pseudo-sustainable apparel exceeds the sum of the increase in consumer utility and the time cost of reporting. Additionally, $R_2 > R_1 + (C_4 - C_3) + I_1 + I_2 + (Q_1 - Q_2)P_1$ indicates that the platform's revenue from loose supervision surpasses the revenue from strict supervision, the difference in regulatory costs between the two approaches, the reputation rewards under strict supervision, the reputation losses under loose supervision, and the differential penalties associated with strict and loose supervision. Ultimately, apparel manufacturers choose to produce pseudo-sustainable apparel, consumers adopt a sustainability-concerned strategy, and the e-commerce platform opts for strict supervision.

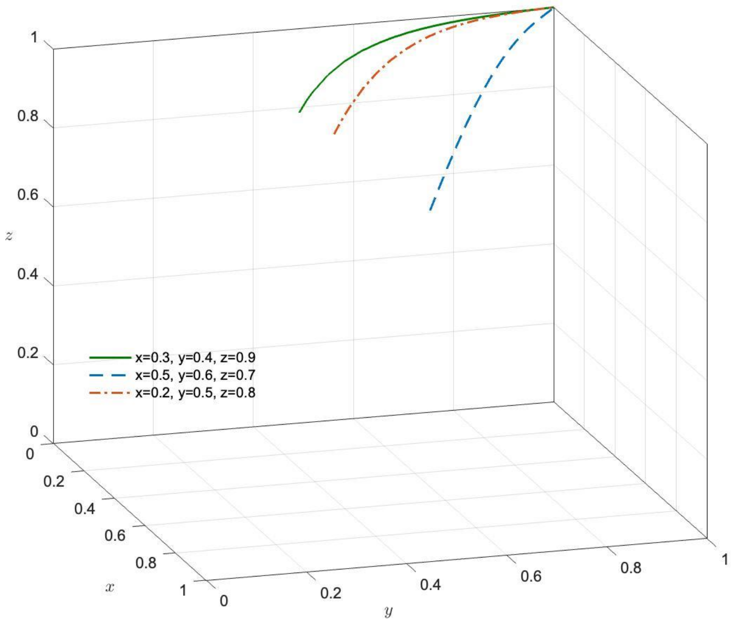


Fig. 6.6 Verification of stability conditions for $W_7(0,1,1)$

6.3.1.6. Verification of stability conditions for $W_8(1,1,1)$

In Table 6.4, the parameter values for W_8 (1,1,1) satisfy the conditions specified in Table 6.3. The initial willingness levels of apparel manufacturers, consumers, and e-commerce platforms are set as (0.3,0.4,0.9), (0.5,0.6,0.7), and (0.2,0.5,0.8), respectively. Based on these values, simulation analyses are conducted to evaluate the behavioral strategies of the three parties under different initial willingness conditions. As shown in Fig. 6.7, despite variations in initial willingness, the behavioral strategies of the three actors ultimately evolve toward $W_8(1,1,1)$.

Under the $W_8(1,1,1)$ scenario, the condition $C_1 < C_2 + I_3 + I_4 + Q_1P_1 + P_2$ indicates that the cost for manufacturers to produce sustainable apparel is lower than the sum of the cost of producing pseudo-sustainable apparel, the reputation rewards for sustainable production, the reputation losses from pseudo-sustainable production, and the regulatory penalties arising from platform inspections and consumer reports. The condition $\lambda U > 0$ suggests that the increase in consumer utility from reporting pseudo-sustainable apparel is positive. Moreover, $R_2 < R_1 + (C_4 - C_3) + I_1 + I_2$ indicates that the platform's revenue from loose supervision is lower than the combined revenue from strict supervision, the difference in regulatory costs, the reputation rewards under strict supervision, and the reputation losses from loose supervision. Ultimately, apparel manufacturers choose to produce sustainable apparel, consumers adopt a sustainability-concerned strategy, and the e-commerce platform chooses strict supervision.

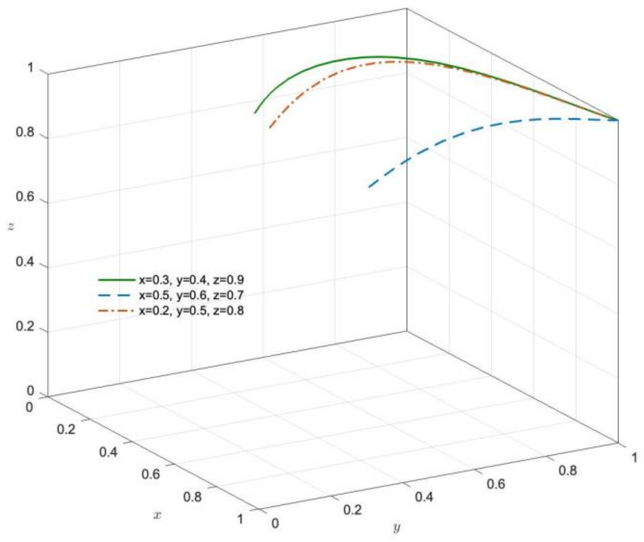


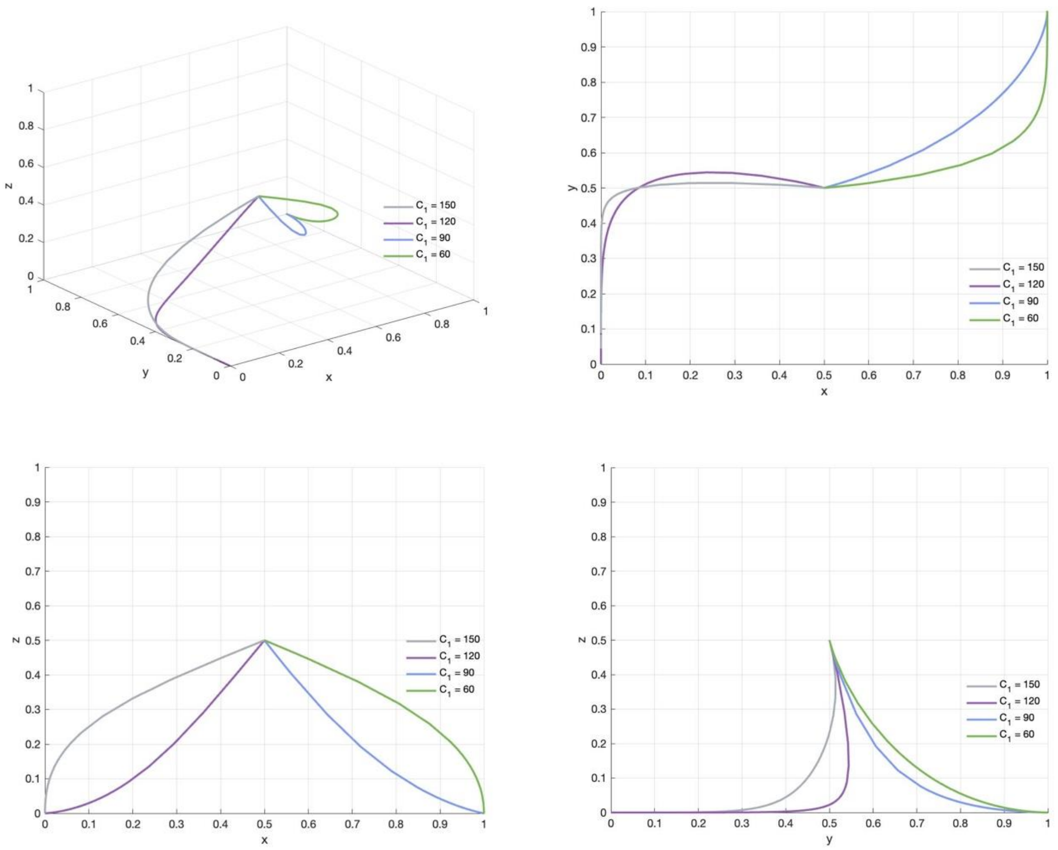
Fig. 6.7 Verification of stability conditions for W_8(1,1,1)

6.3.2. Influence of relevant factors on strategic choices of stakeholders

The previous section has verified the stability conditions of scenarios W_1 (0,0,0), W_3 (0,0,1), W_5 (0,1,0), W_6 (1,1,0), W_7 (0,1,1), and W_8 (1,1,1). This section further explores how the cost C_1 incurred by apparel enterprises in producing sustainable apparel, the time C_5 borne by consumers when reporting to the platform, the revenue R_2 gained by the platform under lax supervision, and the reward R received by consumers for reporting pseudo-sustainable apparel influence the evolutionary dynamics of the system.

6.3.2.1. Impact of the cost of producing sustainable apparel on system evolution

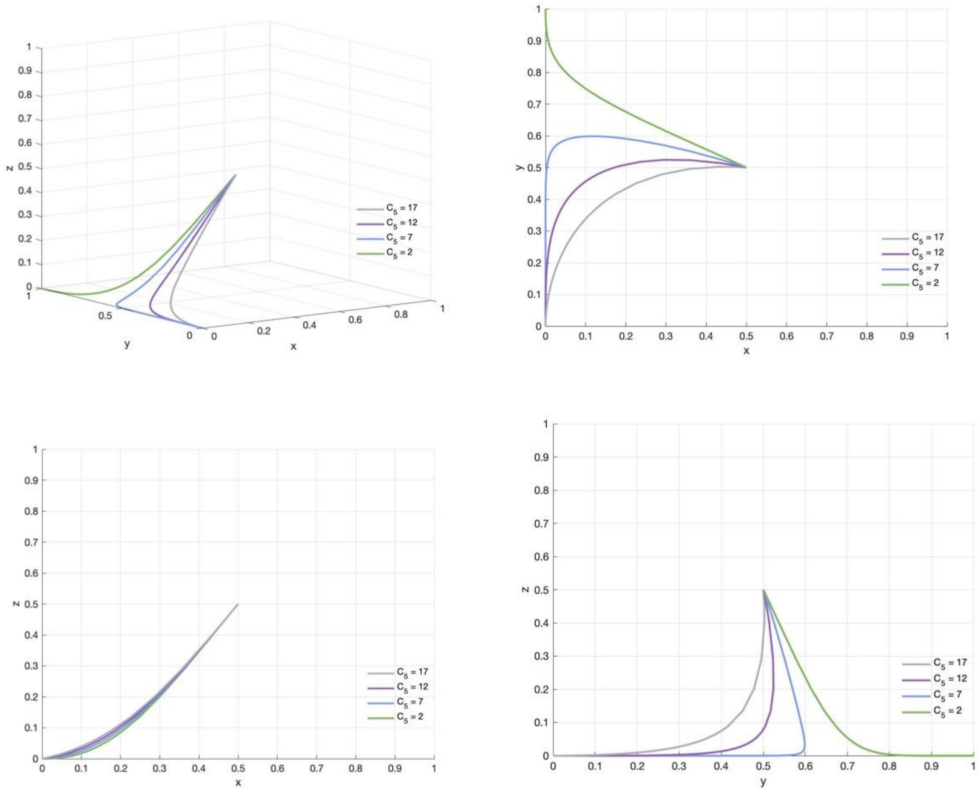
Keeping other parameters constant, the initial willingness levels of apparel enterprises, consumers, and e-commerce platforms are all set to 0.5 in scenario W_1 (0,0,0). Assuming that the cost C_1 of producing sustainable apparel by apparel enterprises takes values of 150, 120, 90, and 60 respectively, the evolutionary paths of the behavioral strategies of apparel enterprises, consumers, and e-commerce platforms are shown in Figs 6.(8-11). The results show that when C_1=150, apparel enterprises choose to produce pseudo-sustainable apparel, consumers adopt the non-concerned strategy regarding sustainability, and e-commerce platforms opt for a lax supervision strategy. When C_1=120, there are no qualitative changes in the strategies of apparel enterprises, consumers, or platforms, but the evolution process slows down. When C_1=90, apparel enterprises choose to produce sustainable apparel, consumers adopt a sustainability-concerned strategy, while e-commerce platforms still adopt a lax supervision strategy. When C_1=60, the evolutionary process toward apparel enterprises producing sustainable apparel and consumers adopting a sustainability-concerned strategy accelerates.



Figs. 6.(8–11) The influence of the cost C_1 of producing sustainable apparel on the behavioral strategies of stakeholders.

6.3.2.2. Impact of the time cost of consumer reporting on system evolution

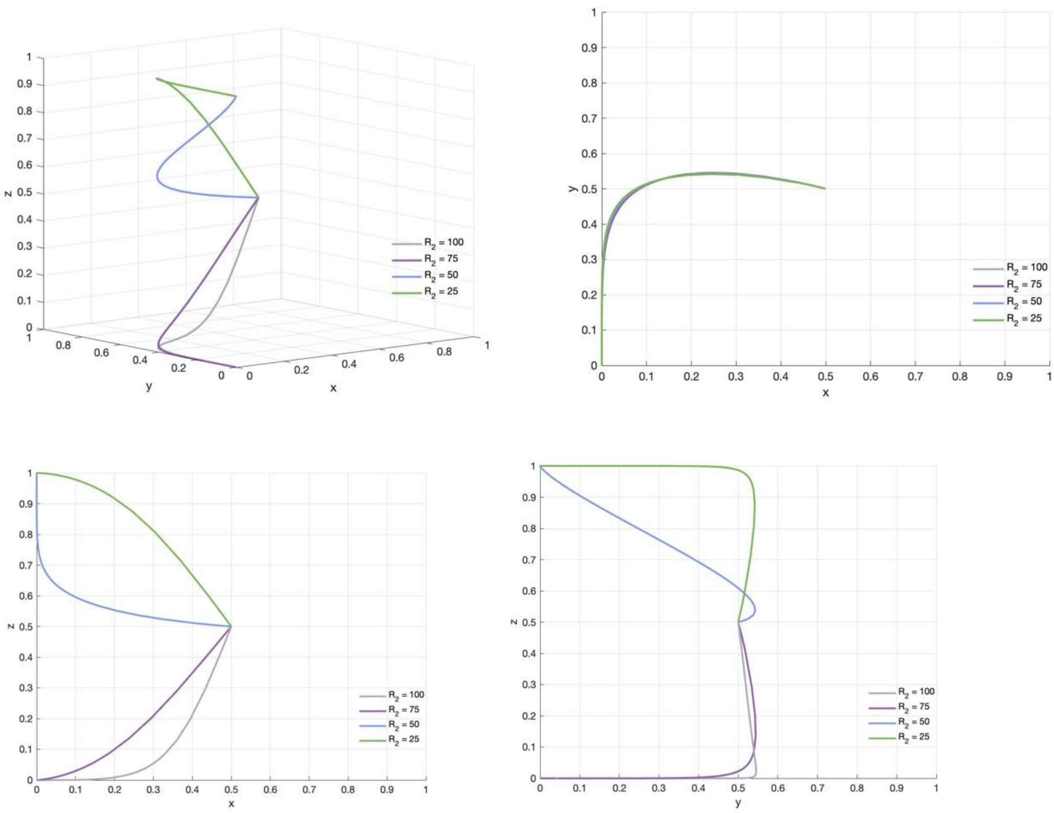
Keeping other parameters constant, the initial willingness levels of apparel enterprises, consumers, and e-commerce platforms are again set to 0.5 in scenario $W_1(0,0,0)$. Assuming that the time cost C_5 incurred by consumers when reporting to the platform takes values of 17, 12, 7, and 2 respectively, the evolutionary paths of the behavioral strategies of apparel enterprises, consumers, and e-commerce platforms are shown in Figs 6.(12–15). The results show that when C_5 =17, apparel enterprises choose to produce pseudo-sustainable apparel, consumers adopt the sustainability-unconcerned strategy, and e-commerce platforms opt for a lax supervision strategy. When C_5=12, 7, there are no qualitative changes in the strategies of apparel enterprises, consumers, or platforms, but the evolutionary process clearly slows down. When C_5=2, consumer behavior changes, consumers begin to adopt the sustainability-concerned strategy.



Figs. 6.(12-15) The influence of the time cost C_5 of consumer reporting on the behavioral strategies of stakeholders

6.3.2.3. Impact of platform revenue under lax supervision on system evolution

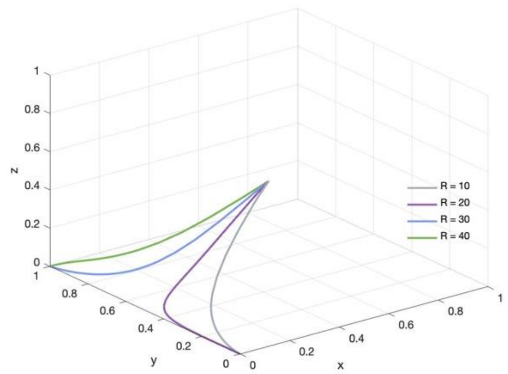
Keeping other parameters constant and continuing with scenario W_1 (0,0,0), the initial willingness levels of apparel enterprises, consumers, and e-commerce platforms are set to 0.5. Assuming that the revenue R_2 gained by the platform under lax supervision takes values of 100, 75, 50, and 25 respectively, the evolutionary paths of the behavioral strategies of apparel enterprises, consumers, and e-commerce platforms are shown in Figs 6.(16–19). The results show that when R_2 =100, apparel enterprises choose to produce pseudo-sustainable apparel, consumers adopt the sustainability-unconcerned strategy, and e-commerce platforms opt for a lax supervision strategy. When R_2=75, there are no qualitative changes in the strategies of apparel enterprises, consumers, or platforms, but the evolution process clearly slows down. When R_2=50, platform behavior changes, and the platform shifts to a strict supervision strategy. When R_2=25, the evolutionary process toward adopting a strict supervision strategy accelerates.

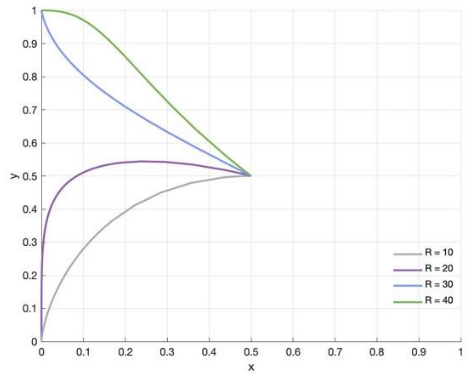


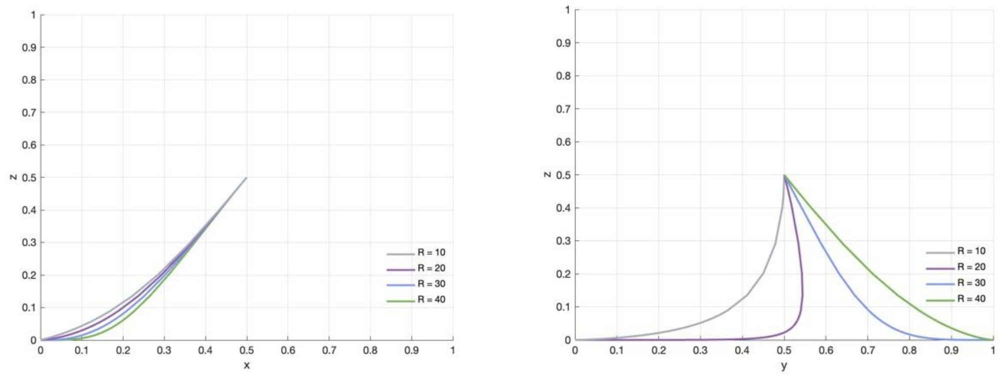
Figs. 6.(16-19) The influence of platform revenue R_2 under lax supervision on the behavioral strategies of stakeholders.

6.3.2.4. Impact of rewards for consumer reporting of pseudo-sustainable apparel on system evolution

Keeping other parameters constant in scenario W_1 (0,0,0), the initial willingness levels of apparel enterprises, consumers, and e-commerce platforms are set to 0.5. Assuming that the reward R received by consumers for reporting pseudo-sustainable apparel to the platform takes values of 10, 20, 30, and 40 respectively, the evolutionary paths of the behavioral strategies of apparel enterprises, consumers, and e-commerce platforms are shown in Figs 6.(20–23). The results show that when R=10, apparel enterprises choose to produce pseudo-sustainable apparel, consumers adopt the sustainability-unconcerned strategy, and e-commerce platforms opt for a lax supervision strategy. When R=20, there are no qualitative changes in the strategies of apparel enterprises, consumers, or platforms, but the evolution process clearly slows down. When R=30, consumer behavior changes, with consumers shifting to a sustainability-concerned strategy. When R =40, the evolutionary process toward consumers adopting the sustainability-concerned strategy accelerates.







Figs. 6.(20-23) The influence of rewards *R* for consumer reporting of pseudo-sustainable apparel on the behavioral strategies of stakeholders.

6.4. Summary

This study, grounded in the context of e-commerce, constructs a tripartite evolutionary game model involving apparel enterprises, consumers, and e-commerce platforms. Using MATLAB for numerical simulation, the stability conditions of the evolutionary game model are verified. The study further explores how the production cost of apparel enterprises, consumers' reporting costs and rewards, and platform revenues influence the strategic choices of each stakeholder. The main conclusions are as follows:

6.4.1. Key findings

The decision of apparel enterprises to produce sustainable apparel is influenced by production costs. When the cost of producing sustainable apparel is significantly higher than that of pseudo-sustainable apparel, enterprises tend to produce pseudo-sustainable apparel to maximize profits. As the production cost of sustainable apparel decreases, enterprises are more inclined to choose sustainable production.

Consumers' strategic behavior is affected by the time cost and reward mechanism associated with reporting pseudo-sustainable apparel. When the reporting cost is high and the reward is low, consumers are more likely to adopt an unconcerned strategy. Conversely, when reporting costs decrease and rewards increase, consumers' sustainability concern becomes more pronounced.

The choice of regulatory intensity by e-commerce platforms depends on the trade-off among regulatory costs, reputational benefits, and economic returns. When a strict regulatory strategy brings long-term reputational gains and higher consumer trust, platforms are more inclined to adopt strict supervision. Otherwise, they tend to opt for lax supervision.

6.4.2. Policy recommendations

Lower the cost of sustainable production to enhance enterprise adoption willingness. Governments can offer incentives such as VAT refunds, equipment upgrade subsidies, and green credit interest discounts to apparel enterprises that use eco-friendly materials, energy-efficient processes, or circular designs, thereby narrowing the cost gap between sustainable and pseudo-sustainable products. Leading enterprises, universities, and research institutes should be encouraged to establish open laboratories for green technologies and patent pools to provide low-barrier technical licensing and training for small and medium-sized brands, forming economies of scale.

Improve consumer reporting incentives and cost compensation mechanisms. E-commerce platforms should place quick-access reporting portals in prominent positions on product pages and commit to providing resolutions within a set timeframe to reduce consumers' information collection and waiting costs. Additionally, rewards should be linked to the severity of violations and diversified through vouchers, points, and green consumption credits to enhance the marginal return of high-quality leads. Platforms must also ensure anonymous handling of whistleblower information and work with regulators to establish exemption mechanisms for blacklisted reporters to alleviate consumer concerns over retaliation.

Strengthen platform accountability and establish positive incentives. Deposit or ecological responsibility fees paid by platforms should be tied to their violation rates in sustainable product categories, with lower violation rates corresponding to more favorable rates, incentivizing proactive compliance. Regulatory agencies and industry associations can regularly publish “Trust Lists” showcasing data such as consumer retention and average transaction value under strict supervision, quantifying reputational benefits. Interfaces for real-time data sharing should be established among governments, platforms, and third-party testing agencies to enforce cross-platform bans on repeat offenders and reduce the economic attractiveness of lax supervision.

7. Conclusions

7.1. Main findings

This study focuses on the sustainable transformation of the apparel industry and investigates the multilateral interaction mechanisms among apparel enterprises, consumers, and e-commerce platforms. By integrating theoretical modeling, numerical simulations, evolutionary game theory, and machine learning algorithms, it systematically analyzes how key factors—such as carbon emission costs, consumer environmental awareness, and government subsidy mechanisms—affect the industry's transformation path from multiple dimensions including production decisions, market structure, consumer behavior, and policy interventions. The main findings are as follows:

First, based on heterogeneous consumer preferences, a systematic production decision model for apparel enterprises was developed. The study reveals the rational choice logic by which firms switch between traditional production, sustainable production, and hybrid strategies under different market conditions and consumer preference structures. Specifically: When consumer willingness to pay (WTP) for sustainable apparel is low and unit production costs are significantly higher than those of traditional apparel, firms tend to exit the market. When WTP is moderate but sustainable apparel still faces a cost disadvantage, firms are more likely to maintain single-product traditional production strategies. As WTP increases and the marginal cost advantage of traditional products erodes, firms are incentivized to shift toward sustainable-only production to expand market share. When consumer

WTP is extremely high and traditional apparel gains a clear cost advantage, firms adopt hybrid strategies to meet diverse market demand while maximizing profit. Additionally, carbon emission costs influence firm strategies.

Second, a hybrid interval carbon price forecasting framework was proposed by integrating XGBoost-based feature selection, an improved NSGA-II multi-objective evolutionary algorithm, and a BiLSTM network. The model: Uses XGBoost to identify key factors driving carbon price fluctuations, removing redundant variables to improve data quality. Applies the improved MSA to optimize the upper and lower bounds of the forecast interval without relying on prior distributional assumptions. Employs BiLSTM to capture the complex nonlinear temporal structure of carbon price sequences. Empirical validation using real-world trading data from China's carbon market shows that this model significantly outperforms traditional interval forecasting methods in both accuracy and robustness.

Third, the study systematically compared two subsidy mechanisms—targeting producers vs. targeting consumers—in the promotion of sustainable apparel. Key findings include: Without subsidies, increased consumer environmental awareness enhances preference for sustainable apparel. Producer-side subsidies are highly effective in promoting sustainable R&D. Consumer-side subsidies, by directly enhancing the utility of purchasing sustainable apparel.

Finally, this study constructs an evolutionary game model involving apparel firms, consumers, and e-commerce platforms to analyze strategic interactions and dynamic evolution in the context of sustainability transformation. Key insights include: Whether firms choose genuine sustainable production is strongly influenced by both production costs and the regulatory environment. When reporting incentives are effective and response mechanisms are transparent, consumers are more likely to participate, forming public pressure and driving the diffusion of sustainable practices.

7.2. Policy recommendations

Based on the above research findings, this study posits that promoting sustainable development in the apparel industry requires more than isolated reforms in single domains. Instead, a systemic policy support framework must be established—one that integrates production, consumption, and platform governance.

To overcome structural barriers such as high costs, high risks, and low consumer acceptance during the early stages of sustainable apparel promotion, it is recommended to implement a phased and actor-specific fiscal subsidy system combining producer-side and consumer-side instruments.

To enhance consumers' ability to identify and proactively purchase sustainable products, regulatory bodies should strengthen information disclosure mechanisms and public education systems. This requires addressing the persistent problems of information asymmetry and limited sustainability awareness.

Regarding platform governance, the role of e-commerce platforms in verifying product compliance and guiding consumer behavior must be reinforced: Clearly define platform accountability for ensuring authenticity and compliance of sustainable product claims within legal and industry standard frameworks.

7.3. Limitations and future research

First, the model relies heavily on the assumption of fully rational behavior. Consumer willingness to pay, firm strategic decision-making, and platform regulatory choices are all modeled under the premise of complete rationality. However, in real-world contexts, individual behaviors are often influenced by cognitive biases, path dependence, emotional preferences, and other non-rational factors, introducing volatility and behavioral inconsistencies. These realities may constrain the model's external validity and predictive capacity. Second, key parameters used in the simulation—such as sustainable apparel production costs and levels of consumer environmental awareness—are primarily derived from secondary literature or industry-level estimates. Due to limitations in data availability, the precision and reliability of certain simulation outcomes may be affected. Third, this study focuses on China's carbon price data and does not extend the analysis to carbon market operations in other countries.

To address these limitations, future research may explore the following directions:

Incorporating behavioral heterogeneity and bounded rationality. To overcome the limitations of the full rationality assumption, future studies are encouraged to adopt modeling approaches that integrate behavioral heterogeneity and bounded rationality. Drawing on insights from behavioral and experimental economics, researchers could incorporate factors such as emotional preferences, social conformity effects, information acquisition costs, and cognitive biases into the decision-making framework.

Enhancing data infrastructure and parameter reliability. Future research should focus on improving the authenticity and dynamism of key model parameters. Collaborations with industry associations, large e-commerce platforms, and certification agencies could help build a multi-source database encompassing sustainable production costs, consumer environmental awareness, carbon label dissemination effectiveness, and more.

Future research could further explore the dynamics of the European carbon price market, which represents one of the most mature and influential carbon trading systems worldwide. By incorporating data from the EU Emissions Trading System (EU ETS), future studies could compare the price formation mechanisms, volatility patterns, and policy impacts between China and Europe.

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