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Research on technological innovation and marketing publicity decision of green intelligent home appliance supply chain considering consumer subsidy and cost-sharing contract

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Under the leadership of China's "dual-carbon" policy, how to reduce energy consumption, reduce carbon emissions, and realize intelligent, low-carbon development has become a key issue faced by the home appliance industry. Studies have shown that green intelligent home appliances can save electricity and reduce carbon emissions. In the context of China's "dual-carbon" goal, this study examines the technological innovation and marketing publicity decisions of the green intelligent home appliance supply chain considering the consumer subsidy and cost-sharing contract. By constructing a three-level supply chain model that includes home appliance manufacturers, retailers, and consumers, we use the Stackelberg game method to study the decision-making models under four scenarios with and without consumer subsidy and cost-sharing contract and consider the impact of consumers' green intelligent preference, consumers' green marketing sensitivity, consumer subsidy and cost-sharing contract on the supply chain optimal decision. Through model solving and further numerical simulation, the results show that 1) the increase of consumers' green intelligent preference and consumers' green marketing sensitivity can produce positive spillover effects and promote the improvement of home appliance manufacturers' technological innovation efforts and retailers' marketing publicity efforts; 2) consumer subsidy is always beneficial for the green intelligent development of the supply chain, which can effectively increase the total revenue of the supply chain; 3) the reasonable cost-sharing ratio can stimulate the enthusiasm of supply chain enterprises to increase technological innovation and marketing publicity investments and increase the total profit of the supply chain. However, the excessive cost-sharing ratio frustrates the enthusiasm of home appliance retailers to participate in the coordination, which results in a decline in the overall benefit of the supply chain; 4) by considering both consumer subsidy and cost-sharing contract, a reasonable level of consumer subsidy and cost-sharing ratio have a better incentive effect on the supply chain members than in the other three scenarios. This study can provide a broader reference for the green intelligent development of China's home appliance industry, which plays an important role in the implementation of China's "dual carbon" goal.

KEYWORDS

"dual carbon" goal, consumer subsidy policy, cost-sharing contract, green intelligent home appliance supply chain, green efforts, Stackelberg game

1 Introduction

In response to the global climate problem, the Chinese government proposed a "dual carbon" goal in 2020 (Hu, 2021) and made a series of policy adjustments around this goal. This is a major challenge and an unprecedented opportunity for the home appliance industry. According to the "Annual Report on the State of Global Energy and Carbon Emissions" released by the International Energy Agency (IEA), home appliances are the second largest source of residential energy consumption and account for over 20% of the electricity consumption, while residential carbon emissions account for more than 30% (Yu, 2021). In addition, according to the statistics of the China Household Electrical Appliances Association (CHEAA) and the current trend of the energy consumption development of home appliances such as refrigerators, microwave ovens, water heaters, and washing machines, it is estimated that the country's hydrofluorocarbon emissions will exceed 25 million tons of CO_2 equivalent by 2030, and this number will further increase to 30 million tons of CO_2 equivalent by 2060 (Deng, 2021). It is a pressing issue for the home appliance industry on how to reduce the energy consumption and carbon emissions of home appliances. Compared with traditional home appliances, green intelligent home appliances can save electricity and reduce carbon emissions. Hu et al. (2023) have also showed that intelligentization is the key to green and low-carbon transformation. Therefore, intelligentization is a necessary path for the transformation and upgradation of the traditional home appliance industry.

Realizing the intelligent manufacturing of home appliances and promoting green and intelligent development of the home appliance industry depend on green technological innovation. In terms of the current development of the home appliance industry, on the whole, the level of green technological innovation in China's home appliance enterprises is low, and there will be much room left to make further progress (Tong, 2020). In addition, it is also very important to do a good job in the marketing of green intelligent home appliances. In the actual marketing environment, the perceived value of a product can be used as a result of consumers' evaluation of the product, which in turn affects their purchase intentions (Li et al., 2020). Alejandre et al. (2022) show that it is better for traditional home appliances to adopt new designs with improved energy-saving models in order to minimize the environmental burden associated with the manufacture of new products. Based on customer-perceived value perspective, Li and Pan (2019) took home appliance retail enterprises as the research object, created a marketing dual-channel synergistic performance evaluation model, and combined it with the fuzzy comprehensive evaluation method to evaluate the O2O marketing synergistic performance of Suning Tesco. The results showed that home appliance retail enterprises have to attach great importance to the pre-sale shopping perception links of consumers in the process of O2O marketing synergistic performance improvement. Jafari (2023) used game theory to conduct research, and the results showed that government support policies can improve the energy saving level of home appliances. Lou and Ma (2018) investigated the complexity of sale and carbon reduction efforts in two parallel appliance supply chain models. We also know that consumer's green preferences influence enterprise decisions (Long et al., 2022). Therefore, the green and intelligent development of the home appliance industry requires upstream and downstream enterprises of the home appliance supply chain to continuously innovate technology, produce green intelligent home appliances, sell green intelligent home appliances to consumers through marketing publicity, cultivate consumers' preference for green intelligent home appliances, and increase consumers' willingness to purchase in future competitions.

However, the input to improve the level of green technological innovation of enterprises will increase enterprises' cost burden, which hinders the green and intelligent development of the industry to a certain extent. So it requires green effort cost-sharing among supply chain enterprises (Ghosh and Shah, 2015). In the study of green supply chain coordinated innovation and cooperation strategy, Sun and Zhang (2020) found that the cost-sharing contract, as an incentive mechanism, can increase the green innovation inputs of supporting enterprises, optimal returns of both parties, and overall returns. Song et al. (2022) showed that the cost-sharing mechanism can coordinate the supply chain participants and make the supply chain members gain higher profits.

In addition, when compared with the price of ordinary home appliances, the price of green intelligent home appliances is also higher, and the higher price will reduce the willingness of consumers to buy. Therefore, countries generally adopt the means of consumer subsidies so as to improve the willingness of consumers to buy. The increasing willingness of consumers to purchase green products will stimulate the market to increase the supply of green products, promote the benign development of the green supply chain, and promote the green transformation and upgradation of the supply chain (Xing et al., 2023). Nie et al. (2021) have evaluated the effectiveness of the current energy-saving subsidy policy to stimulate the purchase of energy-saving household appliances. Song et al. (2019) established a game model in which the government provides subsidies to consumers who use green products and found that the policy can promote the consumption of green products to an optimal level, and high-income groups preferred the government to provide subsidies for green products.

On the basis of previous studies, from the perspective of the green intelligent home appliance supply chain, this study analyzes and discusses the rationality and necessity of home appliance enterprises to increase technological innovation and marketing publicity, and in the four scenarios with and without consumer subsidy and cost-sharing contract, further explores the impact of consumers' green intelligent preference, consumers' green marketing sensitivity, and consumer subsidy and cost-sharing contract on the optimal decision-making of the supply chain. The conclusions of this study to some extent verifies the effectiveness of consumer subsidy and cost-sharing contract in promoting green intelligent development of the home appliance industry, which can provide some references for future government policy formulation, a win–win cooperation among home appliance enterprises, and green intelligent development of the home appliance industry.

The main contributions are as follows: first, we establish a three-level green intelligent home appliance supply chain model comprising manufacturers, retailers, and consumers and at the same time incorporate technological innovation and marketing publicity into demand function, as well as study the optimal decision-making of the supply chain under different scenarios and use the Hessian matrix to find the possibility of the existence of the optimal strategy; second, the impact of consumers' green intelligent preference, consumers' green marketing sensitivity, and consumer subsidy and cost-sharing contract on manufacturers' technological innovation, retailers' marketing publicity, and the total profit of the supply chain is comprehensively considered; finally, through the establishment of the Stackelberg game model to analyze different situations, it further broadens the research ideas of the green intelligent home appliance supply chain, enriches related research theories, and provides a little reference for the green intelligent development of the home appliance industry.

2 Literature review

The research related to this study mainly focuses on three aspects: consumer subsidies, cost-sharing contracts, and the home appliance industry and its supply chain. In this section, we will review the relevant literature and point out how our study differs from them.

2.1 Consumer subsidies

In terms of related research on consumer subsidy policies, some scholars have argued the rationality of consumer subsidies. Yang and Zhao (2015) argued that subsidies for energy-saving products can be deducted from the selling price of the products, which can directly reduce the expenditure of consumers on purchasing the products, guide consumers to support low-carbon products, and enable producers to produce low-carbon products or even zero-emission products. Zhao and Wang (2018) reviewed carbon emission reduction policies in the consumption area such as carbon tax, trading mechanism, and subsidies and compared them in three aspects: efficiency, effectiveness, and fairness; they found that the subsidy policy on the consumption side can help consumers choose low-carbon products or even zero-emission products, which in turn leads to energy-saving production. Li and Wang (2023) demonstrated the necessity of implementing subsidy programs in promoting EV sales and identified the optimal subsidies under various market conditions. Some scholars have also studied the effects of consumer subsidies. Huang et al. (2013) studied government subsidies for consumers purchasing electric vehicles, and the results showed that consumer subsidy policies can significantly increase the sales of electric vehicles, which effectively reduces environmental pollution. Sun and Yu (2018) separately established a two-stage game model under two subsidy policies of the government that subsidizes green producers and consumers. It is found that government subsidizing consumers can increase the consumer demand for green products to a greater extent and bring greater benefits to green producers. Long et al. (2022) explored the joint effect of the dominance structure, green sensitivity, and green preference on the manufacturing closed-loop supply chain and showed that increasing government price subsidies is more favorable to market demand and social welfare. In addition, some scholars have also compared consumer subsidies with other subsidies. By using a game theoretical approach, Bian et al. (2020) analyzed the effects of consumer and manufacturer subsidies on incentives for investing in emission reduction technologies in the manufacturing sector. Hong et al. (2021) examined the impact of corporate subsidies and consumer subsidies on green products. Khosroshahi et al. (2021) developed a three-stage game model with three subsidy policies, namely, government subsidies for manufacturers, retailers, and consumers, respectively, and studied the impact of government subsidies and CSR on supply chain pricing, greenness, and transparency. Xu and Duan (2022) explored optimal pricing and green investment strategies of green products under three kinds of subsidy policies, namely, manufacturer subsidy, retailer subsidy, and consumer subsidy, and investigated the conditions for the adoption of blockchain technology (Xu and He, 2022). Wang and Wang (2020) applied a game theory approach and focused on investigating how sales efforts and different government subsidies promoted manufacturers' carbon emission reductions. Pan et al. (2023) constructed three game models that included no government subsidy, government subsidy to manufacturers, and government subsidy to consumers to study the effects of retailers' fairness concerns and channel competition on the dual-channel green supply chains' optimal decision-making and social welfare under different government subsidy strategies.

2.2 Cost-sharing contracts

The study of green supply chain decision-making problems under cost-sharing contracts is also relatively abundant. Yenipazarli (2017) examined the impact of cost-sharing contracts on downstream retailers' incentives for upstream manufacturers to innovate. Yi and Li (2018a) studied cost-sharing contracts for energy saving and emissions reduction of a supply chain under the conditions of government subsidies and the carbon tax. Chakraborty et al. (2019) introduced the cost-sharing contract into retailer-led quality innovation cooperation, achieving the improvement of supply chain members and overall profits. Xu et al. (2020) studied product greenness and pricing decisions under three green cost-sharing models in the competitive green supply chain environment. Ma et al. (2020) studied cost-sharing contracts for achieving green supply chain coordination based on confidence level rules under uncertain information. Hu et al. (2020) considered a joint competitive innovation game model in which suppliers dominated and retailers shared innovation costs and compared the effects of two research and development (R&D) cost-sharing ratios proposed by retailers on suppliers' incentives to innovate. Sharm and Jain (2021) studied cost-sharing contract when the dominant player had fairness preferences under different power structures of the green supply chain. Liu (2021) comparatively investigated the effects of product greenness and big data investment costs on green supply chain pricing strategies and profits under three cost-sharing models, considering both big data investment costs and green technology R&D costs. Qin et al. (2021) investigated the game of environmental cost allocation in the green supply chain under fair preferences. The results showed that retailers' participation in environmental cost allocation increases the greenness level of products and make the whole supply chain Pareto optimal and strong fairness preferences of the manufacturers weakens the positive effect of retailers' participation in the supply chain on cost allocation. Lin and Liu (2022) explored the effects of government subsidies and firms' cost sharing on the level of green efforts, pricing strategies, and profits in the green supply chain. Fan et al. (2023) considered how to design a quality cost-sharing contract to incentivize product quality level improvement and integrate resources (Xu et al., 2021; Xu et al., 2022a). Wang and Wang (2020) studied the long-term cooperative emission reduction, low-carbon publicity, and government subsidies in a low-carbon supply chain based on a differential game model. Lou et al. (2020) investigated low-carbon emission reduction and publicity decision-making of supply chain in the context of different leaders. Meanwhile, they also studied the decision-making model of supply chain enterprises to encourage enterprises to carry out emission reduction innovation through contracts. Yu et al. (2020) explored the effectiveness of carbon emission reduction investment behavior in supply chain enterprises based on cost-sharing coordination under cost subsidy.

2.3 Home appliance industry and its supply chain

At present, the following scholars have conducted relevant research on the technological innovation and marketing publicity in the home appliance industry and home appliance supply chain. Yan (2010) pointed out that it is urgent for home appliance enterprises to implement green procurement, which is of great significance in improving product competitiveness and implementing sustainable development, and green technology innovation is the key link of implementing green procurement. Shen et al. (2012) have detailed how to use experiential marketing to create corporate value in downstream supply chain management of home appliance enterprises. Ma and Zhao (2013) studied the impact of trade-in subsidy on the production and consumption of home appliances. The results showed that policy incentives can effectively boost manufacturers' profits and further promote the research and development of green appliances. Guo and Zheng (2019) in a systematic discussion on the capability upgrading problems faced by home appliance firms in the context of open innovation have made it clear that catching up with technology is the key (Xu et al., 2022b; Xu and Wei, 2023). Yu et al. (2021) constructed a manufacturer-led dual-channel low-carbon supply chain competition and cooperation game and analyzed the effects of energy efficiency ratio, retailers' sales effort, consumption channel preferences, and manufacturers' fairness concerns on manufacturers' and retailers' decisions and revenue. Lv and Huang (2021) provided an empirical test for the conclusion that demand promotes innovation in the home appliance industry, whereby foreseeable future market demand both effectively promotes innovation inputs and enhances innovation outputs. Li et al. (2021) constructed a tripartite game model among the government, home appliance enterprises, and consumers and found that the government's carbon emission reduction subsidies can improve the innovation ability of enterprises. Lei et al. (2022) showed that income growth will drive home appliance enterprises to transform toward intelligentization and low carbonization.

Finally, we have made a detailed comparison of the related literature, which is shown in Table 1. We can find that the aforementioned studies have conducted a great deal of research on the supply chain and home appliance industry and have achieved certain results. However, most of the current literature discusses manufacturers' technological innovation or retailers' marketing publicity from the perspective of the home appliance industry and home appliance supply chain, and few scholars consider both at the same time and incorporate them into the demand function. In terms of government subsidies to the home appliance industry, there are few literature studies on consumer subsidies. However, in real life, the government subsidizes consumers who buy appliances that meet green and intelligent requirements. Therefore, it is necessary to study the impact of consumer subsidies on green intelligent home appliance supply chain decisions. On this basis, studies combining cost-sharing contract with technological innovation, marketing publicity, and consumer subsidy are even rarer. The Stackelberg game model is widely used in the supply chain's optimal decision problem and further through numerical simulation to validate the results of the model and increase the reliability of the model and its conclusions; for example, Lou and Ma's (2018) research on the decision-making of sales and carbon reduction effort in the home appliance supply chain and Cao et al.'s (2020) comparative study of supply chain green effort decisions based on different government subsidy strategies. Therefore, based on the aforementioned analysis, this study starts from the green intelligent home appliance supply chain, incorporates technological innovation and marketing publicity into the demand function, considers the impact of consumers' green intelligent preferences, consumers' green marketing sensitivity, and consumer subsidy and cost-sharing contract and explores technological innovation and marketing publicity issues of the home appliance industry. The main research problem of this study is to explore the optimal decision-making problem for each subject of the green intelligent home appliance supply chain under the four models, verify the effectiveness of the Chinese government's consumer subsidy policy, and draw conclusions based on the model's results and numerical simulation to provide a reference for practice.

3 Problem description and model assumptions

3.1 Problem description

In order to explore technological innovation and marketing publicity decisions of the green intelligent home appliance supply chain by considering consumer subsidy and cost-sharing contract, this study constructs a three-level green intelligent home appliance supply chain model that consists of manufacturers who carry out technological innovation, retailers who are responsible for marketing publicity, and consumers. In this supply chain, home appliance manufacturers are in the dominant position followed by home appliance retailers, constituting the Stackelberg game. Home appliance manufacturers produce green intelligent home appliances with unit cost c through technological innovation and sell them to home appliance retailers at wholesale price ω, and home appliance

TABLE 1 Comparison of the literature.

	Consumer subsidy	Cost-sharing contract	Focus
Sun and Zhang (2020)	—	✓	Cost-sharing contract; green innovation input; profit
Song et al. (2022)	—	✓	Cost-sharing contract; price; green product quality; profit
Xing et al. (2023)	✓	—	Consumer subsidy; manufacturers' green innovation efforts; price; profit
Song et al. (2019)	✓	—	Government subsidy; taxation; consumer preference; income
Sun and Yu (2018)	✓	—	Government subsidy; consumer preference; green degree; profit
Long et al. (2022)	✓	—	Consumer subsidy; green preference; green investment; green sensitivity; price; social welfare
Khosroshahi et al. (2021)	✓	—	Government subsidy; CSR; price; greening degree; transparency level
Xu and Duan (2022)	✓	—	Government subsidy; blockchain technology; price; greenness investment
Wang and Wang (2020)	✓	—	Government subsidy; retailers' sales effort; consumer preference; carbon emission reduction; social welfare
Pan et al. (2023)	✓	—	Government subsidy; fairness-concerns; price; green degree; social welfare
Li et al. (2021)	—	✓	Cost-sharing contract; government subsidy; carbon tax; energy-saving level; carbon-emission level
Xu et al. (2020)	—	✓	Cost-sharing contract; pricing strategy; product greenness
Ma et al. (2020)	—	✓	Cost-sharing contract; uncertainty information; confidence level
Sharm and Jain (2021)	—	✓	Cost-sharing contract; fairness; price; product green level; profit
Liu (2021)	—	✓	Cost-sharing contract; big data information cost; product green degree; pricing strategy; profit
Lin and Liu (2022)	✓	✓	Government subsidy; cost-sharing contract; manufacturers' green efforts level; pricing strategy; profit
Our study	✓	✓	Consumer subsidy; cost-sharing contract; consumer green intelligent preference; consumer green marketing sensitivity; green technological innovation efforts level; green marketing publicity efforts level; profit

retailers sell them to consumers at retail price p through marketing publicity to maximize profits. However, the ever-increasing costs of technological innovation hinder manufacturers from investing in technological innovation efforts. In order to encourage home appliance manufacturers to increase technological innovation investment, home appliance retailers have the motivation to share some technological innovation costs of home appliance manufacturers, thereby improving decision-making levels and achieving supply chain coordination. The government provides subsidies to consumers who purchase green intelligent home appliances to increase the product market demand, thereby affecting the optimal decision-making of home appliance supply chain members. In addition, we assume that consumers have green preferences, and their demands are affected by the level of product technology innovation, product marketing publicity, and product prices.

Therefore, this study uses the Stackelberg game method to analyze and compare game models of the green intelligent home appliance supply chain under four scenarios without considering consumer subsidy and cost-sharing contract (Model D), considering the consumer subsidy (Model M), considering cost-sharing contract (Model C), and considering both consumer subsidy and cost-sharing contract (Model U) and focuses on the impact of consumers' green intelligent preference, consumers' green marketing sensitivity, consumer subsidy and cost-sharing contract on the supply chain upstream and downstream home appliance enterprises technological innovation and marketing publicity and the total profit of the supply chain. The green intelligent home appliance supply chain game model is shown in Figure 1.

3.2 Model hypotheses

Assumption 1. In order to improve the green intelligent level of home appliances, home appliance manufacturers increase the technological innovation investment. We assume that the technological innovation costs of home appliance manufacturers is $\eta\varphi^2/2$ (Xue et al., 2019; Lin and Liu, 2022), where η is the cost coefficient of technological innovation and φ is the level of technological innovation efforts.

Assumption 2. In order to guide consumers' preference for green intelligent home appliances, home appliance retailers increase marketing publicity investments. We assume that the marketing publicity costs of home appliance retailers is $\lambda A^2/2$ (Lou and Ma, 2018; Yuan et al., 2022), where λ is the cost coefficient of marketing publicity and A is the level of marketing publicity efforts.

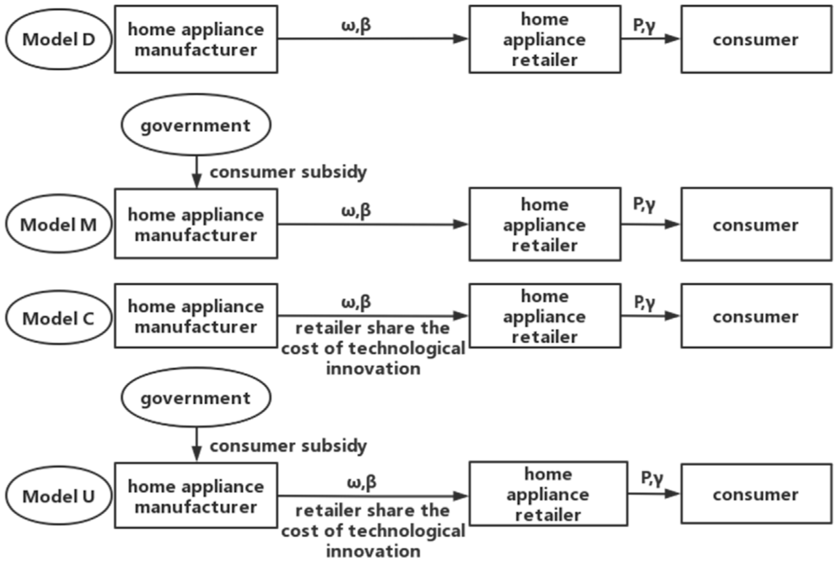

FIGURE 1
Green intelligent home appliance supply chain game model diagram.

Assumption 3. Members of the home appliance supply chain produce green intelligent home appliances according to the quantity determined by the market demand function, and the products can be completely cleared. We assume that the green intelligent home appliance market demand function is $a - bp + \beta\varphi + \gamma A$ (Yi and Li, 2018a; Sun and Zhong, 2023), where a is the market capacity, b is the consumer's price sensitivity coefficient, p is the retail price of the product market, β is consumer's green intelligent preference coefficient, and γ is consumer's green marketing sensitivity coefficient.

Assumption 4. In order to encourage consumers to purchase green intelligent home appliances, the government subsidizes for consumers an amount of s, which will directly affect the price of products purchased by consumers, and the actual purchase price of consumers is p – s (Wang and Wang, 2023; Xing et al., 2023). For example, Shanghai provides consumers with a one-time subsidy of 10% of the payment amount and up to 1,000 yuan for personal consumption such as purchasing green intelligent home appliances.

Assumption 5. In order to encourage home appliance manufacturers to increase technological innovation investment, home appliance retailers have the motivation to share some technological innovation costs of home appliance manufacturers, thereby improving the decision-making levels and achieving supply chain coordination. When home appliance manufacturers and retailers reach a cost-sharing contract, the ratio of technological innovation costs share by retailers is θ (Yi and Li, 2018b; Ma et al., 2020) and the ratio share by manufacturers is (1 – θ).

3.3 Model parameters

All parameters involved in this study and their definitions are summarized in Table 2.

4 Decision model and result analysis of green intelligent home appliance supply chain

4.1 Decentralized decision-making of green intelligent home appliance supply chain (Model D)

First, home appliance manufacturers decide the level of technological innovation efforts and wholesale prices of green intelligent home appliances, while retailers then decide the retail prices and level of marketing publicity efforts of green intelligent home appliances, and the goal of both the decisions is to maximize their own profits. The profit function of home appliance manufacturers and retailers is as follows:

$$\pi_M^d = (\omega - c)(a - bp + \beta\varphi + \gamma A) - \frac{1}{2}\eta\varphi^2, \quad (1)$$

$$\pi_R^d = (p - \omega)(a - bp + \beta\varphi + \gamma A) - \frac{1}{2}\lambda A^2. \quad (2)$$

We use the reverse induction method to calculate the second-order partial derivative of and on Formula 2 and get the Hessian matrix as follows: $H = \begin{pmatrix} -2b & \gamma \\ \gamma & -\lambda \end{pmatrix} = -\gamma^2 + 2b\lambda$.

Therefore, when $-2b < 0$ and $-\gamma^2 + 2b > 0$, the profit function of home appliance retailers is a concave function of p and A, and there is an optimal solution. Let the first derivation be equal to 0 and be solved simultaneously to get

$$p_d^* = \frac{-\omega\gamma^2 + (a + b\omega + \beta\varphi)\lambda}{-\gamma^2 + 2b\lambda}, \quad (3)$$

$$A_d^* = \frac{(a - b\omega + \beta\varphi)\gamma}{-\gamma^2 + 2b\lambda}. \quad (4)$$

Then, substitute (3–4) into (1) and calculate the second-order partial derivative of ω and φ, respectively; the Hessian matrix is obtained as follows:

TABLE 2 Symbol parameter.

Symbolic parameter	Parameter meaning
c	Unit production cost of green intelligent home appliances
ω	Wholesale price of green intelligent home appliances
p	Retail price of green intelligent home appliances
a	Market capacity of green intelligent home appliances
β	Consumer's green intelligent preference coefficient
b	Consumer's price sensitivity coefficient
φ	Technological innovation efforts level of home appliance manufacturers
η	Technological innovation cost coefficient
θ	Home appliance retailers' share ratio of technological innovation costs
s	Amount of price subsidy provided by the government to consumers for purchasing unit green intelligent home appliances
A	Marketing publicity effort level of home appliance retailers
λ	Marketing publicity cost coefficient
γ	Consumer's green marketing sensitivity coefficient
π_M	Profits of home appliance manufacturers
π_R	Profits of home appliance retailers
π_{SC}	Total profit in the supply chain
Annotation	$\theta \in (0,1)$, $a > 0$, and $s > 0$

$$H = \begin{pmatrix} \frac{-4b^2\lambda}{-2\gamma^2+4b\lambda} & \frac{2b\lambda\beta}{-2\gamma^2+4b\lambda} \\ \frac{2b\lambda\beta}{-2\gamma^2+4b\lambda} & \frac{2\eta(\gamma^2-2b\lambda)}{-2\gamma^2+4b\lambda} \end{pmatrix} = \frac{b^2\lambda(-2\eta\gamma^2+4b\eta\lambda-\lambda\beta^2)}{(\gamma^2-2b\lambda)^2}.$$

Therefore, when $\frac{2b^2\lambda}{\gamma^2-2b\lambda}<0$ and $\frac{b^2\lambda(-2\eta\gamma^2+4b\eta\lambda-\lambda\beta^2)}{(\gamma^2-2b\lambda)^2}>0$, the profit function of home appliance manufacturers is a concave function of ω and φ, and there is an optimal solution. Let the first derivation be equal to 0, and when solved simultaneously, we can get

$$\omega_d^* = \frac{(a+bc)\eta(-\gamma^2+2b\lambda)-bc\lambda\beta^2}{b(-2\eta\gamma^2+4b\eta\lambda-\lambda\beta^2)}, \tag{5}$$

$$\varphi_d^* = \frac{(a-bc)\lambda\beta}{-2\eta\gamma^2+4b\eta\lambda-\lambda\beta^2}. \tag{6}$$

By substituting (5–6) into (3–4), the values of optimal decision variables p and A are obtained as follows:

$$p_d^* = \frac{a\eta(\gamma^2-3b\lambda)+bc(\eta(\gamma^2-b\lambda)+\lambda\beta^2)}{b(2\eta(\gamma^2-2b\lambda)+\lambda\beta^2)}, \tag{7}$$

$$A_d^* = \frac{(-a+bc)\eta\gamma}{2\eta(\gamma^2-2b\lambda)+\lambda\beta^2}. \tag{8}$$

By substituting (5–8) into (1–2), we obtain the profit function of home appliance manufacturers and retailers as follows:

$$\pi_M^{d*} = \frac{(a-bc)^2\eta\lambda}{-4\eta\gamma^2+8b\eta\lambda-2\lambda\beta^2}, \tag{9}$$

$$\pi_R^{d*} = \frac{(a-bc)^2\eta^2\lambda(-\gamma^2+2b\lambda)}{2(2\eta(\gamma^2-2b\lambda)+\lambda\beta^2)^2}. \tag{10}$$

At the same time, we can get the optimal profit function of the home appliance supply chain as follows:

$$\pi_{SC}^{d*} = \pi_M^{d*} + \pi_R^{d*} = \frac{(a-bc)^2\eta\lambda(-3\eta\gamma^2+6b\eta\lambda-\lambda\beta^2)}{2(2\eta(\gamma^2-2b\lambda)+\lambda\beta^2)^2}. \tag{11}$$

Only when $\omega_d^*, \varphi_d^*, p_d^*, A_d^*, \pi_M^{d*}, \pi_R^{d*}, \pi_{SC}^{d*} > 0$, home appliance manufacturers and retailers will conduct investment and manufacturing activities, so $a-bc>0$ should be satisfied with the following same reasoning.

4.2 Decentralized decision-making of green intelligent home appliance supply chain considering consumer subsidy (Model M)

In order to encourage consumers to purchase green intelligent home appliances, the government subsidizes consumers with an amount of s, which will directly affect the price of products purchased by consumers, and the actual purchase price of consumers is $p-s$. The profit function of home appliance manufacturers and retailers is as follows:

$$\pi_M^m = (\omega-c)(a-b(p-s)+\beta\varphi+\gamma A)-\frac{1}{2}\eta\varphi^2, \tag{12}$$

$$\pi_R^m = (p-\omega)(a-b(p-s)+\beta\varphi+\gamma A)-\frac{1}{2}\lambda A^2. \tag{13}$$

We use the reverse induction method to obtain the optimal decision of ω, φ, p, and A as follows:

$$\omega_m^* = \frac{(a + b(s + c))\eta(-\gamma^2 + 2b\lambda) - bc\lambda\beta^2}{b(-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2)}, \tag{14}$$

$$\varphi_m^* = \frac{(a + b(-c + s))\lambda\beta}{-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2}, \tag{15}$$

$$p_m^* = \frac{\eta(a + bs)(\gamma^2 - 3b\lambda) + bc(\eta(\gamma^2 - b\lambda) + \lambda\beta^2)}{b(2\eta(\gamma^2 - 2b\lambda) + \lambda\beta^2)}, \tag{16}$$

$$A_m^* = \frac{-(a + b(-c + s))\eta\gamma}{2\eta(\gamma^2 - 2b\lambda) + \lambda\beta^2}. \tag{17}$$

By substituting (14–17) into (12–13), we obtain the following profit functions of home appliance manufacturers and retailers

$$\pi_M^{m^*} = \frac{(a + b(-c + s))^2\eta\lambda}{-4\eta\gamma^2 + 8b\eta\lambda - 2\lambda\beta^2}, \tag{18}$$

$$\pi_R^{m^*} = \frac{(a + b(-c + s))^2\eta^2\lambda(-\gamma^2 + 2b\lambda)}{2(2\eta(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \tag{19}$$

At the same time, we get the following optimal profit function of the home appliance supply chain:

$$\pi_{SC}^{m^*} = \pi_M^{m^*} + \pi_R^{m^*} = \frac{(a + b(-c + s))^2\eta\lambda(-3\eta\gamma^2 + 6b\eta\lambda - \lambda\beta^2)}{2(2\eta(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \tag{20}$$

The derivation process is similar to that mentioned in Section 4.1 and is hence not repeated here.

Corollary 1. In decision-making Model M, under the consumer subsidy policy, the first-order partial derivative of s is obtained as follows:

$$\frac{\partial\omega_m^*}{\partial s} > 0, \frac{\partial p_m^*}{\partial s} > 0, \frac{\partial A_m^*}{\partial s} > 0, \frac{\partial\varphi_m^*}{\partial s} > 0, \frac{\partial\pi_M^{m^*}}{\partial s} > 0, \frac{\partial\pi_R^{m^*}}{\partial s} > 0, \frac{\partial\pi_{SC}^{m^*}}{\partial s} > 0;$$

Corollary 1 shows that government subsidies to consumers can encourage them to purchase more green intelligent home appliances, and then home appliance manufacturers and retailers can make more green efforts and choose to increase wholesale and retail prices of green intelligent home appliances to make up for their green investments. It can be seen that the consumer subsidy policy can promote the overall low-carbon green benefits and income of the home appliance supply chain.

Proof of Corollary 1. The proof process is as follows:

$$\frac{\partial\omega_m^*}{\partial s} = \frac{b\eta(-\gamma^2 + 2b\lambda)}{b(-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2)} > 0, \frac{\partial p_m^*}{\partial s} = \frac{b\eta(\gamma^2 - 3b\lambda)}{b(2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)} > 0,$$

$$\frac{\partial A_m^*}{\partial s} = \frac{-b\eta\gamma}{2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2} > 0, \frac{\partial\varphi_m^*}{\partial s} = \frac{b\lambda\beta}{-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2} > 0,$$

$$\frac{\partial\pi_M^{m^*}}{\partial s} = \frac{2b(a - bc + bs)\eta\lambda}{-4\eta\gamma^2 + 8b\eta\lambda - 2\lambda\beta^2} > 0, \frac{\partial\pi_R^{m^*}}{\partial s} = \frac{2b(a - bc + bs)\eta^2\lambda(-\gamma^2 + 2b\lambda)}{2(2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)^2} > 0,$$

$$\frac{\partial\pi_{SC}^{m^*}}{\partial s} = \frac{2b(a - bc + bs)\eta\lambda(-3\eta\gamma^2 + 6b\eta\lambda - \lambda\beta^2)}{2(2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)^2} > 0.$$

Through the algebraic operation, we found that when government provides subsidies to consumers, with the increase of consumer subsidy, there is an increase in the wholesale price and technological innovation efforts of the green intelligent home appliances produced by home appliance manufacturers, and the retail price and marketing publicity efforts of home appliance retailers increase. At the same time, the profits of home appliance manufacturers and retailers, and the total profit of the supply chain increase accordingly. When $-\gamma^2 + 2b\lambda > 0$ and $-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2 > 0$, the aforementioned relationship is established.

4.3 Decentralized decision-making of green intelligent home appliance supply chain considering cost-sharing contract (Model C)

In order to encourage home appliance manufacturers to increase technological innovation investment, home appliance retailers have the motivation to share some technological innovation costs of home appliance manufacturers, thereby improving the decision-making levels and achieving supply chain coordination. When home appliance manufacturers and retailers reach a cost-sharing contract, the ratio of technological innovation costs share by retailers is θ and the ratio share by manufacturers is $(1 - \theta)$. The profit function of home appliance manufacturers and retailers is as follows:

$$\pi_M^c = (\omega - c)(a - bp + \beta\varphi + \gamma A) - \frac{1}{2}(1 - \theta)\eta\varphi^2, \tag{21}$$

$$\pi_R^c = (p - \omega)(a - bp + \beta\varphi + \gamma A) - \frac{1}{2}\lambda A^2 - \frac{1}{2}\theta\eta\varphi^2. \tag{22}$$

We use the reverse induction method to calculate the second-order partial derivative of Formula 22 and get the Hessian matrix as follows: $H = \begin{pmatrix} -2b & \gamma \\ \gamma & -\lambda \end{pmatrix} = -\gamma^2 + 2b\lambda$.

Therefore, when $-2b < 0$ and $-\gamma^2 + 2b > 0$, the profit function of home appliance retailers is a concave function of p and A, and there is an optimal solution. Let the first derivation equal to zero and be solved simultaneously to get

$$p_c^* = \frac{-\omega\gamma^2 + (a + b\omega + \beta\varphi)\lambda}{-\gamma^2 + 2b\lambda}, \tag{23}$$

$$A_c^* = \frac{(a - b\omega + \beta\varphi)\gamma}{-\gamma^2 + 2b\lambda}. \tag{24}$$

We then substitute (23–24) into (21) and calculate the second-order partial derivative of its ω and φ, and the Hessian matrix obtained is as follows:

$$H = \begin{pmatrix} \frac{2b^2\lambda}{\gamma^2 - 2b\lambda} & \frac{b\lambda\beta}{-\gamma^2 + 2b\lambda} \\ \frac{b\lambda\beta}{-\gamma^2 + 2b\lambda} & (-1 + \theta)\eta \end{pmatrix} = \frac{b^2\lambda(2\eta(-1 + \theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2)}{(\gamma^2 - 2b\lambda)^2}.$$

Therefore, when $\frac{2b^2\lambda}{\gamma^2 - 2b\lambda} < 0$ and $\frac{b^2\lambda(2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2)}{(\gamma^2 - 2b\lambda)^2} > 0$, the profit function of home appliance manufacturers is a concave function of ω and φ, and there is an optimal solution. Let the first derivation equal to zero and be solved simultaneously to get

$$\omega_c^* = \frac{(a + bc)\eta(-\gamma^2 + 2b\lambda)(-1 + \theta) + bc\lambda\beta^2}{b(-2\eta(-1 + \theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)}, \tag{25}$$

$$\varphi_c^* = \frac{(a - bc)\lambda\beta}{2\eta(-1 + \theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2}. \tag{26}$$

Substituting (25–26) into (23–24), the values of the optimal decision variables p and A are obtained as follows:

$$p_c^* = \frac{a\eta(\gamma^2 - 3b\lambda)(-1+\theta) + bc\eta(\gamma^2 - b\lambda)(-1+\theta) - bc\lambda\beta^2}{b(2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2)}, \quad (27)$$

$$A_c^* = \frac{(a-bc)\eta\gamma(-1+\theta)}{-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2}. \quad (28)$$

Substituting (25–28) into (21–22), we obtain the profit function of appliance manufacturers and retailers as follows:

$$\pi_M^{c*} = \frac{(a-bc)^2\lambda\eta(-1+\theta)}{2\lambda\beta^2 - 4\eta(-1+\theta)(\gamma^2 - 2b\lambda)}, \quad (29)$$

$$\pi_R^{c*} = \frac{(a-bc)^2\lambda\eta(-\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\theta\beta^2)}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \quad (30)$$

At the same time, we get the optimal profit function of the home appliance supply chain as follows:

$$\pi_{SC}^{c*} = \pi_M^{c*} + \pi_R^{c*} = \frac{(a-bc)^2\lambda\eta(-3\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\beta^2)}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \quad (31)$$

Corollary 2. In the decision-making model C, under the condition of cost sharing of technological innovation, the first-order partial derivative of θ is obtained as follows:

$$\frac{\partial\omega_c^*}{\partial\theta} > 0, \frac{\partial p_c^*}{\partial\theta} > 0, \frac{\partial A_c^*}{\partial\theta} > 0, \frac{\partial\varphi_c^*}{\partial\theta} > 0;$$

Corollary 2 shows that home appliance retailers share the cost of technological innovation, which reduces the cost of technological innovation investment of home appliance manufacturers, and then home appliance manufacturers make more green efforts to improve the innovation level of green intelligent home appliances. At the same time, to ensure profits, home appliance manufacturers choose to increase the wholesale price of green intelligent home appliances. With the rise in the innovation level of green intelligent home appliances, market demand expands, prompting home appliance retailers to improve the level of marketing publicity efforts. At the same time, in order to ensure profits, home appliance retailers tend to increase the retail price of green intelligent home appliances. It can be seen that the introduction of the cost-sharing contract can further increase the enthusiasm in the production and investment of node enterprises in the home appliance supply chain.

Proof of Corollary 2. The proof process is as follows:

$$\frac{\partial\omega_c^*}{\partial\theta} = \frac{(a-bc)b\lambda\beta^2\eta(-\gamma^2 + 2b\lambda)}{(b(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2))^2} > 0,$$
$$\frac{\partial p_c^*}{\partial\theta} = \frac{(bc-a)b\lambda\beta^2\eta(\gamma^2 - 3b\lambda)}{(b(2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2))^2} > 0,$$
$$\frac{\partial A_c^*}{\partial\theta} = \frac{(a-bc)\eta\gamma\lambda\beta^2}{(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2} > 0,$$
$$\frac{\partial\varphi_c^*}{\partial\theta} = \frac{-(a-bc)\lambda\beta 2\eta(\gamma^2 - 2b\lambda)}{(2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2)^2} > 0.$$

Through the algebraic operation, we found that when home appliance retailers share the cost of technological innovation efforts, with the increase in cost-sharing ratio, the wholesale price and technological innovation efforts of the green intelligent home appliances produced by home appliance manufacturers, and the retail price and marketing publicity efforts of home appliance retailers increase. When $-\gamma^2 + 2b\lambda > 0$ and $2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2 > 0$, the aforementioned relationship is established.

Corollary 3. In the decision-making model C, under the condition of cost sharing of technological innovation, the first-order partial derivative of θ is obtained as follows:

When $\theta < \frac{\lambda\beta^2}{4\eta(-\gamma^2+2b\lambda)}$, $\frac{\partial\pi_R^{c*}}{\partial\theta} > 0$, oppose $\frac{\partial\pi_R^{c*}}{\partial\theta} < 0$; $\frac{\partial\pi_M^{c*}}{\partial\theta} > 0$;when $\theta < \frac{1}{3}$, $\frac{\partial\pi_{SC}^{c*}}{\partial\theta} > 0$, oppose $\frac{\partial\pi_{SC}^{c*}}{\partial\theta} < 0$;

Corollary 3 shows that when home appliance retailers share the cost of technological innovation, as the cost-sharing ratio increases, the cost of technological innovation for home appliance manufacturers gradually decrease and their profits gradually increase. Under a reasonable cost-sharing ratio, although the home appliance retailers bear a part of the technological innovation investment cost of home appliance manufacturers, it promotes the production enthusiasm of home appliance manufacturers, expands market demand, and increases profits of home appliance retailers. However, when the cost-sharing ratio is very high, the cost of home appliance retailers exceeds the profits, and their participation enthusiasm decreases, resulting in a decrease in the overall profits of the home appliance supply chain.

Proof of Corollary 3. The proof process is as follows:

$$\frac{\partial\pi_R^{c*}}{\partial\theta} = \frac{(a-bc)^2\lambda^2\beta^2\eta(-\lambda\beta^2 - 4\theta\eta(\gamma^2 - 2b\lambda))}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^3},$$
$$\text{when } \theta < \frac{\lambda\beta^2}{4\eta(-\gamma^2 + 2b\lambda)}, \frac{\partial\pi_R^{c*}}{\partial\theta} > 0, \text{ oppose } \frac{\partial\pi_R^{c*}}{\partial\theta} < 0;$$
$$\frac{\partial\pi_M^{c*}}{\partial\theta} = \frac{(a-bc)^2 2\lambda^2\beta^2\eta}{(2\lambda\beta^2 - 4\eta(-1+\theta)(\gamma^2 - 2b\lambda))^2} > 0;$$
$$\frac{\partial\pi_{SC}^{c*}}{\partial\theta} = \frac{(a-bc)^2\lambda^2\beta^2\eta^2(-\gamma^2 + 2b\lambda)(6(-1+\theta) + 4)}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^3},$$
$$\text{when } \theta < \frac{1}{3}, \frac{\partial\pi_{SC}^{c*}}{\partial\theta} > 0, \text{ oppose } \frac{\partial\pi_{SC}^{c*}}{\partial\theta} < 0.$$

Through the algebraic operation, we found that when home appliance retailers share the cost of technological innovation, the profits of home appliance manufacturers increase with the increase in cost-sharing ratio; when $\theta < \frac{\lambda\beta^2}{4\eta(-\gamma^2+2b\lambda)}$, the retailer's profit increases, and when $\theta > \frac{\lambda\beta^2}{4\eta(-\gamma^2+2b\lambda)}$, the retailer's profit decreases; when $\theta < 1/3$, the total profit of the supply chain increases, and when $\theta > 1/3$, the total profit of the supply chain decreases. When $-\gamma^2 + 2b\lambda > 0$ and $2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2 > 0$, the aforementioned relationship is established.

4.4 Decentralized decision-making of green intelligent home appliance supply chain considering consumer subsidy and cost-sharing contract (Model U)

We further analyze the impact of consumer subsidy and cost-sharing contract on the optimal decision-making of home appliance manufacturers and retailers. The profit function of home appliance manufacturers and retailers is as follows:

$$\pi_M^u = (\omega - c)(a - b(p - s) + \beta\varphi + \gamma A) - \frac{1}{2}(1-\theta)\eta\varphi^2, \tag{32}$$

$$\pi_R^u = (p - \omega)(a - b(p - s) + \beta\varphi + \gamma A) - \frac{1}{2}\lambda A^2 - \frac{1}{2}\theta\eta\varphi^2. \tag{33}$$

We use the reverse induction method to obtain the optimal decision of ω, φ, p, and A as follows:

$$\omega_u^* = \frac{(a + b(c+s))\eta(-\gamma^2 + 2b\lambda)(-1+\theta) + bc\lambda\beta^2}{b(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)}, \tag{34}$$

$$\varphi_u^* = \frac{(a + b(-c+s))\lambda\beta}{2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2}, \tag{35}$$

$$p_u^* = \frac{\eta(a + bs)(\gamma^2 - 3b\lambda)(-1+\theta) + bc\eta(\gamma^2 - b\lambda)(-1+\theta) - bc\lambda\beta^2)}{b(2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2)}, \tag{36}$$

$$A_u^* = \frac{(a + (-c+s)b)\eta\gamma(-1+\theta)}{-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2}. \tag{37}$$

By substituting (34–37) into (32–33), we obtain the profit function of home appliance manufacturers and retailers as follows:

$$\pi_M^{u^*} = \frac{(a + b(-c+s))^2\lambda\eta(-1+\theta)}{2\lambda\beta^2 - 4\eta(-1+\theta)(\gamma^2 - 2b\lambda)}, \tag{38}$$

$$\pi_R^{u^*} = \frac{(a + b(-c+s))^2\lambda\eta(-\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\theta\beta^2}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \tag{39}$$

At the same time, we can get the optimal profit function of the home appliance supply chain as follows:

$$\pi_{SC}^{u^*} = \pi_M^{u^*} + \pi_R^{u^*} = \frac{(a + b(-c+s))^2\lambda\eta(-3\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\beta^2)}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2}. \tag{40}$$

The derivation process is similar to that mentioned in Section 4.3 and is hence not repeated here.

Corollary 4. For the home appliance supply chain, under a certain cost-sharing ratio, the benefits brought by decentralized decision-making in the green intelligent home appliance supply chain with the consumer subsidy are better than those brought by decentralized decision-making in the green intelligent home appliance supply chain without consumer subsidy, that is, $\pi_{SC}^{u^*} > \pi_{SC}^{c^*}$.

Proof of Corollary 4. The proof process is as follows:

$$\pi_{SC}^{u^*} - \pi_{SC}^{c^*} = \frac{bs(bs + 2(a - bc))\lambda\eta(-3\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\beta^2)}{2(-2\eta(-1+\theta)(\gamma^2 - 2b\lambda) + \lambda\beta^2)^2} > 0.$$

When $-\gamma^2 + 2b\lambda > 0$ and $-3\eta(\gamma^2 - 2b\lambda)(-1+\theta)^2 - \lambda\beta^2 > 0$, the aforementioned relationship is established.

Corollary 5. For home appliance manufacturers, under a certain amount of consumer subsidies, the benefits brought by decentralized decision-making in the green intelligent home appliance supply chain with cost-sharing contract are better than those brought by decentralized decision-making in the green intelligent appliance supply chain without cost-sharing contract, that is, $\pi_M^{u^*} > \pi_M^{m^*}$.

Proof of Corollary 5. The proof process is as follows:

$$\pi_M^{u^*} - \pi_M^{m^*} = \frac{-2(a + b(-c+s))^2\lambda^2\beta^2\eta\theta}{(2\lambda\beta^2 - 4\eta(-1+\theta)(\gamma^2 - 2b\lambda))(-4\eta\gamma^2 + 8b\eta\lambda - 2\lambda\beta^2)} > 0.$$

When $-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2 > 0$ and $2\eta(-1+\theta)(\gamma^2 - 2b\lambda) - \lambda\beta^2 > 0$, the aforementioned relationship is established.

Corollary 6. In the decision-making model D, the first-order partial derivative of β and γ is obtained as follows:

$$\frac{\partial\varphi_d^*}{\partial\beta} > 0, \frac{\partial A_d^*}{\partial\beta} > 0, \frac{\partial\varphi_d^*}{\partial\gamma} > 0, \frac{\partial A_d^*}{\partial\gamma} > 0.$$

Corollary 6 shows that with the increase of consumers' green intelligence preference and green marketing sensitivity, that is, the more the consumers prefer green intelligent home appliances, the more the consumers will want to buy them, which will promote home appliance manufacturers to improve the level of product technological innovation and produce green intelligent home appliances, and promote retailers to improve the level of marketing publicity efforts to meet the market demand.

Proof of Corollary 6. The proof process is as follows:

$$\frac{\partial\varphi_d^*}{\partial\beta} = \frac{(a - bc)\lambda(-2\eta\gamma^2 + 4b\eta\lambda + \lambda\beta^2)}{(-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2)^2} > 0;$$
$$\frac{\partial\varphi_d^*}{\partial\gamma} = \frac{-(a - bc)\lambda\beta(-4\eta\gamma)}{(-2\eta\gamma^2 + 4b\eta\lambda - \lambda\beta^2)^2} > 0;$$
$$\frac{\partial A_d^*}{\partial\beta} = \frac{-(-a + bc)\eta\gamma 2\lambda\beta}{(2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)^2} > 0;$$
$$\frac{\partial A_d^*}{\partial\gamma} = \frac{(-a + bc)\eta(-2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)}{(2\eta\gamma^2 - 4b\eta\lambda + \lambda\beta^2)^2} > 0.$$

Through the algebraic operation, we found that with the increase in consumers' green intelligence preference and green marketing sensitivity, the level of technological innovation efforts and marketing publicity efforts increases. When $-2\eta(\gamma^2 - 2b\lambda) + \lambda\beta^2 > 0$, the aforementioned relationship is established. Similarly, in decision Model M, Model C, and Model U, with the increase in consumers' green intelligence preference and green marketing sensitivity, the level of technological innovation efforts and marketing publicity efforts increases. The proof process is not repeated here.

5 Numerical simulation

In order to better verify the changing relationship between the parameters, this section compares and analyzes the parameters by assigning them. First, we describe and explain the parameters involved in the article in the third part of the problem description and model assumptions. Then, based on these descriptions, we refer to the previous relevant literature and set the values of the fixed parameters (Lou and Ma, 2018; Ma et al., 2020; Xing et al., 2023). These values are as follows: $a = 40$, $b = 1$, $c = 10$, $\eta = 1$, $\lambda = 0.8$, $\beta = 0.7$, and $\gamma = 0.5$.

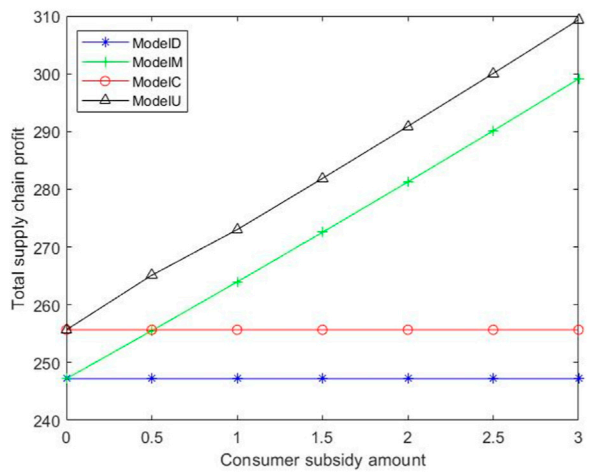

FIGURE 2
Impact of consumer subsidy amount on the total profit of the green intelligent home appliance supply chain.

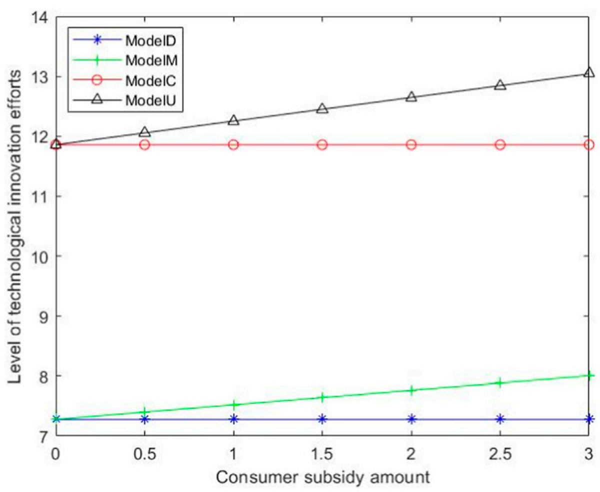

FIGURE 3
Impact of consumer subsidy amount on the level of technological innovation efforts.

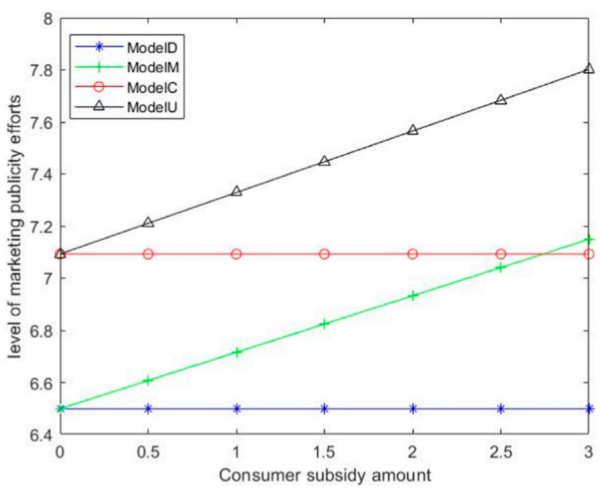

FIGURE 4
Impact of consumer subsidy amount on the level of marketing publicity efforts.

5.1 Impact of consumer subsidy amount *s* on green intelligent home appliance supply chain decision-making

Within the range of conditions that satisfy the existence of an optimal solution, when $\theta = 0.33$ is taken, we analyze the impact of the consumer subsidy amount on green intelligent home appliance supply chain decision-making. As shown in Figure 2, from Model M and Model U, it is seen that the total profit of the home appliance supply chain increases with the increase in consumer subsidy amount. As shown in Figure 3, from Model M and Model U, it is seen that the level of technological innovation efforts of home appliance manufacturers tend to increase as consumer subsidy amount increases. As shown in Figure 4, from Model M and Model U, it is seen that the level of marketing publicity efforts of home appliance retailers is positively correlated with the consumer subsidy amount. That is to say, as the amount of government subsidy to consumers increases, the total profit of the supply chain, level of technological innovation efforts, and level of marketing publicity efforts increase accordingly, all of which are greater than they are in the case of Model D. Therefore, the consumer subsidy policy can promote the overall green benefits and income of the home appliance supply chain. Corollary 1 is verified. In addition, Figures 2–4 show that Model U is always higher than Model M, Model C, and Model D, which shows that when the cost-sharing contract is introduced into the home appliance supply chain, the technological innovation efforts of home appliance manufacturers, marketing publicity efforts of home appliance retailers, and total profit of the supply chain in the consumer subsidy scenario are better than that of the other three scenarios. Therefore, consumer subsidy further improves the overall benefit of the home appliance supply chain. Corollary 4 is verified. Finally, Figure 2 shows that when $s \in (0.5,3)$, Model M is higher than Model C. Figure 4 shows that when $s \in (2.738, 3)$, Model M is higher than Model C. In Figure 3, Model C is always higher than Model M. This suggests that in the two decision models that consider the impact of consumer subsidy on green intelligent home appliance supply chain decision-making and the impact of cost-sharing contract on green intelligent home appliance supply chain decision-making, consumer subsidy has a more significant impact on the total profit of the supply chain and the level of retailer's marketing publicity efforts than it does on the cost-sharing contract; and the cost-sharing contract has a more significant impact on the level of the manufacturer's technological innovation efforts than it does on consumer subsidy.

5.2 Impact of cost-sharing ratio θ on green intelligent home appliance supply chain decision-making

Within the range of conditions that satisfies the existence of the optimal solution, when $s = 3$ is taken, the impact of the cost-sharing

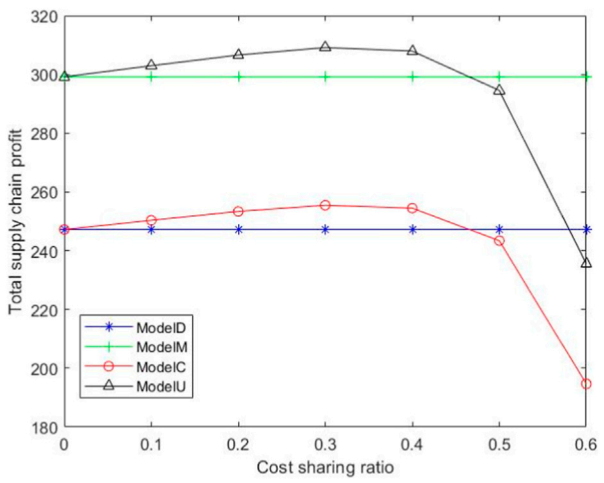

FIGURE 5
Impact of cost-sharing ratio on the total profit of the green intelligent home appliance supply chain.

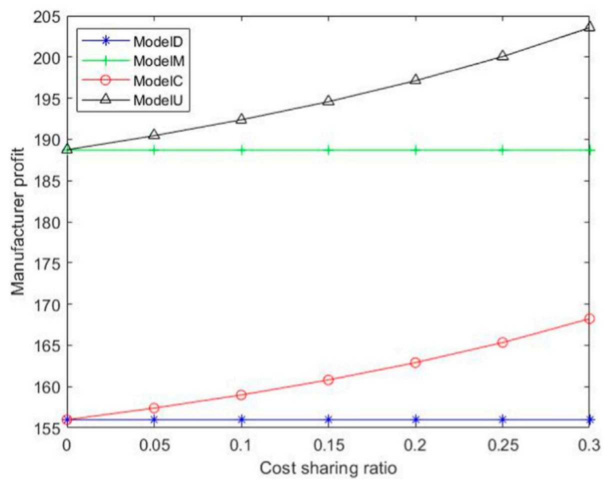

FIGURE 6
Impact of cost-sharing ratio on the profit of the home appliance manufacturer.

ratio on the home appliance supply chain decision-making is analyzed. Figure 5 shows that in Model C and Model U, the total profit of the home appliance supply chain first increases and then decreases with the increase in cost-sharing ratio, until it is lower than the total profit of the supply chain in Model D and Model M. At $\theta = 0.33$, the total supply chain profit is maximum. Figure 6 shows that in Model C and Model U, the profit of home appliance manufacturers increases with the increase in cost-sharing ratio, and the two are positively correlated. Corollary 3 is verified. In addition, Figure 6 shows that Model U is higher than Model M, Model C, and Model D, which shows that when the government provides a certain amount of consumer subsidy, the profit of the home appliance manufacturers in the cost-sharing contract scenario is better than it is in the other three scenarios. Corollary 5 is verified. It can be seen from Figures 7, 8 that in Model C and Model U, respectively, with the increase in cost-sharing ratio, the technology innovation efforts of home appliance manufacturers and the marketing publicity efforts of home appliance retailers increase accordingly, both of which are greater than in Model D. Therefore, the introduction of the cost-sharing contract can further increase the enthusiasm of production and investment of node enterprises in the home appliance supply chain. Corollary 2 is verified. In addition, Figures 7, 8 show that Model U is always higher than Model M, Model C, and Model D, which shows that when the government provides a certain amount of consumer subsidy, the technological innovation efforts of home appliance manufacturers and the marketing publicity efforts of home appliance retailers in the cost-sharing contract scenario are better than they are in the other three scenarios. Therefore, the cost-sharing contract can promote the level of green efforts in the home appliance supply chain. Finally, Figure 7 shows that within a reasonable cost-sharing ratio, Model C is higher than Model M when the cost-sharing ratio is greater than 0.079. In Figures 5, 8, Model M is higher than Model C. This suggests that in the two decision models that consider the impact of consumer subsidy on green intelligent home appliance supply chain decision-making and the impact of the cost-sharing contract on green intelligent home appliance supply chain

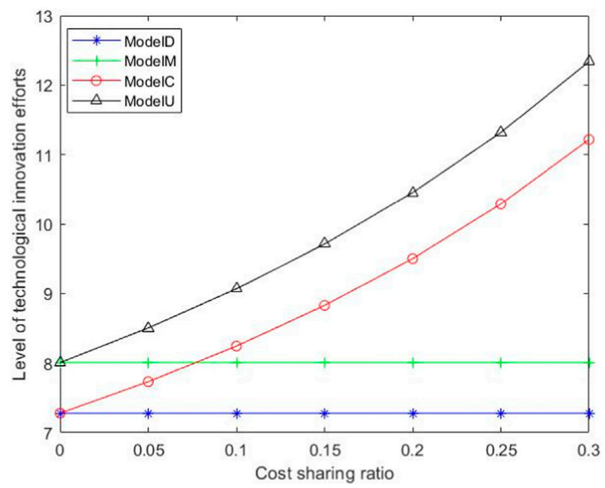

FIGURE 7
Impact of cost-sharing ratio on the level of technological innovation efforts.

decision-making, consumer subsidy has a more significant impact on the total profit of the supply chain and the level of retailer's marketing publicity efforts than it does on the cost-sharing contract; and the cost-sharing contract has a more significant impact on the level of the manufacturer's technological innovation efforts than it does on consumer subsidy.

5.3 Impact of consumers' green intelligent preference β and green marketing sensitivity γ

It can be seen from Figures 9A, B that in Model D, Model M, Model C, and Model U, with an increase of consumers' green

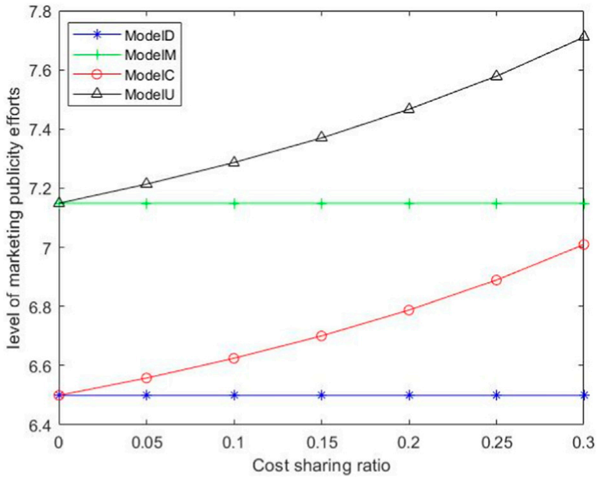

FIGURE 8
Impact of cost-sharing ratio on the level of marketing publicity efforts.

intelligence preference, the technology innovation efforts of home appliance manufacturers and the marketing publicity efforts of home appliance retailers increase accordingly. At the same time, it can be seen from Figures 10A, B that in Model D, Model M, Model C, and Model U, technology innovation efforts and marketing publicity efforts show the same trend of change with the increase of consumers' green marketing sensitivity. That is, consumers' green intelligence preference and consumers' green marketing sensitivity produce spillover benefits, which benefit all enterprises in the home appliance supply chain. Therefore, as consumers increasingly favor green intelligent home appliance products produced by home appliance manufacturers, the market demand gradually increases, and home appliance retailers also increase their marketing publicity efforts to attract more consumers and obtain higher profits. Similarly, as consumers become more sensitive to the marketing publicity of home appliance retailers, the market demand gradually increases, and home appliance manufacturers become more active in improving the innovation level of green intelligent home appliance products to meet consumer green intelligent demands, thereby increasing profits. Corollary 6 is verified.

6 Conclusion

This article starts from the perspective of technological innovation and marketing publicity of the green intelligent home appliances supply chain, and it uses the Stackelberg game method to conduct research. With and without consumer subsidy and cost-sharing contract, a three-level supply chain model comprising home appliance manufacturers, retailers, and consumers is constructed to study technological innovation and marketing publicity decisions within the supply chain. The study discusses the impact of consumers' green intelligent preference, consumers' green marketing sensitivity, and consumer subsidy and cost-sharing contract on the optimal decision-making of supply chain members.

The results of the model analysis show that: (1) the increase in consumers' green intelligent preference and consumers' green marketing sensitivity produces positive spillover effects and promotes the improvement of home appliance manufacturers' technological innovation efforts and retailers' marketing publicity efforts. Sun and Yu (2018) and Sharm and Jain (2021) have also confirmed that consumer's green preference has a positive impact on manufacturers' green efforts of manufacturers. (2) Consumer subsidy has an incentive effect on the home appliance supply chain. Specifically, consumer subsidy can effectively increase not only the level of technological innovation efforts of home appliance manufacturers and total profit of the supply chain (Long et al., 2022; Pan et al., 2023) but also the level of marketing publicity efforts of home appliance retailers (Yuan et al., 2022). (3) When home appliance retailers adopt cost-sharing contract to help home appliance manufacturers reduce the cost pressure of technological innovation inputs, a reasonable cost-sharing ratio promotes both parties in the supply chain to participate in green activities, stimulate the enthusiasm of supply chain enterprises to increase technological innovation (Qin et al., 2021) and marketing publicity (Sharma and Jain, 2021) investment, increase the total profit of the supply chain, promote the green intelligent development of the home appliance industry, and achieve the coordinated development of economy and environment. However, when the cost-sharing ratio is very high, the operating costs of home appliance retailers are very high, and the enthusiasm for participating in coordination is frustrated, which reduces the overall benefit of the supply chain. Therefore, a reasonable cost-sharing ratio should be formulated to achieve the optimal decision-making effect of the supply chain. (4) When consumer subsidy and cost-sharing contract coexist, a reasonable consumer subsidy amount and cost-sharing contract have a better impact on the total profit of the home appliance supply chain, the level of the manufacturer's technological innovation efforts, and the level of the retailer's marketing publicity efforts than they do in the other three scenarios. In addition, in the two decision models that consider the impact of consumer subsidy on green intelligent home appliance supply chain decision-making and the impact of cost-sharing contract on green intelligent home appliance supply chain decision-making, consumer subsidy has a more significant impact on the total profit of the supply chain and the level of retailer's marketing publicity efforts than does cost-sharing contract; and cost sharing contract has a more significant impact on the level of manufacturer's technological innovation efforts than does consumer subsidy.

Based on the aforementioned research conclusions, the following management enlightenment is put forward, providing a broader reference for the green intelligent development of China's home appliance industry. First, the government should increase policy support and provide subsidies to consumers who buy green intelligent home appliances, so as to help home appliance enterprises to improve their return on investments, shorten the economic return cycle, and expand their market scale, thereby raising the enthusiasm of home appliance enterprises in technological innovation and marketing publicity, and thus promoting the green intelligent development of the home appliance industry. Second, for home appliance enterprises, promoting the production and sales of green intelligent home appliances requires the joint efforts of home appliance

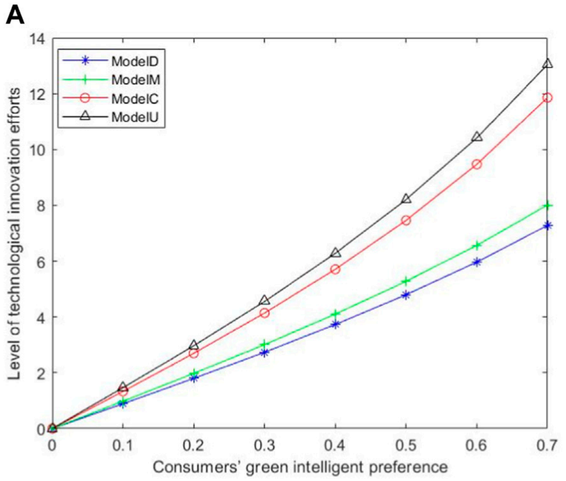

FIGURE 9
Impact of consumers' green intelligent preference on the level of technological innovation efforts and marketing publicity efforts. **(A)** Impact of consumers' green intelligent preference on the level of technological innovation efforts. **(B)** Impact of consumers' green intelligent preference on the level of marketing publicity efforts.

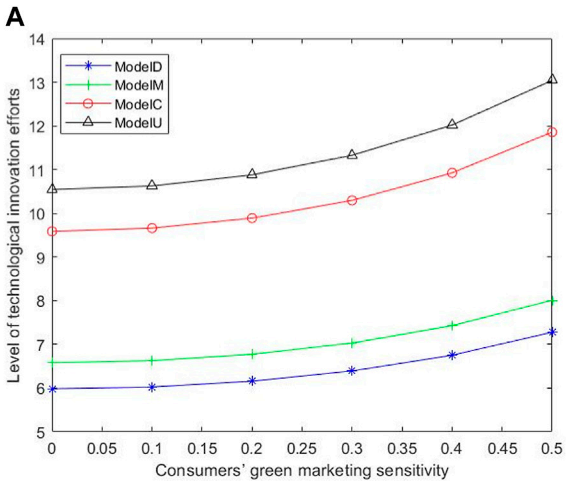

FIGURE 10
Impact of consumers' green marketing sensitivity on the level of technological innovation efforts and marketing publicity efforts. **(A)** Impact of consumers' green marketing sensitivity on the level of technological innovation efforts. **(B)** Impact of consumers' green marketing sensitivity on the level of marketing publicity efforts.

manufacturers and home appliance retailers. While home appliance manufacturers carry out green technological innovations, home appliance retailers are required to attract more consumers through marketing publicity. On this basis, the introduction of the cost-sharing contract into the home appliance supply chain and a reasonable cost-sharing ratio will further enhance the earnings of enterprises in the home appliance supply chain. Therefore, home appliance enterprises should strengthen the cooperation with each other, further integrate internal resources, and take the initiative to meet market demand to achieve a win–win situation. Finally, the government and home appliance enterprises should actively promote green intelligent home appliances to consumers, cultivate consumers' green intelligent preferences, and jointly create a strong atmosphere for the pursuit of green and low-carbon development in the whole society so that the concept of green and intelligent sustainable development gets deeply rooted in people's hearts and minds, which can in turn promote an increase in the benefits of the home appliance supply chain and the continuous improvement of the quality of the ecological environment.

Limitations and future prospects resulting from this study: first, this study deals with optimal decision-making of the green intelligent home appliance supply chain under consumer subsidy policy, without involving the government to provide a certain proportion of the subsidies to home appliance manufacturers and retailers. In future research, it can explore how to achieve a win–win cooperation among all parties in the green intelligent home appliance supply chain while providing government subsidies to home appliance manufacturers and retailers, further improving the innovation level of green intelligent home appliance products, thus proposing a better government subsidy program. Second, this study uses a linear function to estimate the market demand of green intelligent home appliances. However, the market demand is affected by many factors, which makes it difficult to predict the demand. We can further consider the optimal decision-making problem of the green intelligent home appliance supply chain under the condition of uncertain demand. Finally, this study does not consider the risk aversion of home appliance manufacturers' technological and retailers' marketing publicity investment activities. In the future, the influence of variables such as the investment risk aversion preference of home appliance enterprises on the green intelligent effort and income of the green intelligent home appliance supply chain can be considered, making the research more detailed and in-depth.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

CC: conceptualization, methodology, manuscript writing–original draft, formal analysis, and funding acquisition. QL: conceptualization, software, and manuscript writing–original draft. QY: software and manuscript writing–review and editing. SL: manuscript writing–review and editing. HZ: funding acquisition, supervision, and manuscript writing–review and editing. XG: manuscript writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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