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China's insurance and green economy development in the context of sustainable development

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China's insurance and green economy development in the context of sustainable development

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The impact of insurance company participation on the capital market's sustainable development—empirical evidence based on investor sentiment and stock price synchronicity

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Given the representativeness and availability of data, this paper selects personal posts from the Oriental Wealth Internet Cafe and Sina Internet Cafe Forum to analyze the mechanism of insurance company participation, investor sentiment, and stock price synchronicity in China. Using a panel of data of listed companies from 2007 to 2018, evidence shows that investor sentiment in the stock market forum will increase the synchronicity of stock prices in the short term, while an insurance company's shareholding effectively reduces the impact of investor sentiment on share price synchronicity which plays a mediator effect; the higher the proportion of the insurance company's shareholdings, the more evident the effect. By conducting counterfactual research, the study found that insurance company participation can reduce the synchronicity of stock price by 0.10435 in a group with high investor sentiment than a group with low investor sentiment. For each investor sentiment group, the higher the proportion of the insurance company's shareholdings, the greater the reduction in the synchronicity of stock prices. The results of this study can be used by national regulatory authorities to formulate policies in the field of e-finance in order to reduce stock price synchronization, stabilize financial markets, and minimize systemic financial risks.

KEYWORDS

investor sentiment, insurance company participation, stock price synchronicity, sustainable development, capital market

1 Introduction

Since China is a new capital market, its stock market development is late, market maturity is low, rules and regulations are not perfect, and irrational investment behavior such as "chasing up and down," "blindly following the trend," and "over-investment," among other kinds, is frequent, resulting in the stock price's normal value deviating from the predicted benchmark. The "same rise and fall" phenomenon is quite pronounced (Li and Myers, 2006), which has a negative impact on the sustainable development and prosperity of the entire capital market. Issues need to be traced back to their source, and edgy market regulations have to be strengthened.

Most of the information in the financial market is obtained from exogenous sources such as social media changes, whose sentiment change is closely related to asset prices; in particular, when sentiment enters the market, investors will have different rational and irrational behaviors because investor decision-making depends on its self-rational assessment of information, and the process of integrating emotional factors into stocks will affect stock prices in the next few days (Sul et al., 2017). Also, personal emotions can influence individual behaviors and decisions, and emotions can be infectious (Nofer and Hinz, 2015; Ruan et al., 2018); with information flowing increasingly faster, the stock price will be more likely to reverse (Andrei and Cujean, 2017), so the interaction between different users in the social network model on different stock forums will affect stock price fluctuations. Thus, these network forums are being increasingly used by investors. International research in this area is extensive, and the stock market forum research has involved a number of forum posts and post content (Antweiler and Frank, 2004; Das and Chen, 2007). At present, Chinese research on the appearance of investor sentiment in stock forum posts is relatively one-sided, and this paper makes an attempt to analyze investor sentiment in the stock market from a different perspective.

In view of various risks present in financial markets, insurance companies, as an important force in the capital market (Talonen et al., 2022), have attracted the attention of all parties. In October 2018, the Chinese Banking Regulatory Commission stated that it will increase the volume of investment provided by insurance funds to listed companies, going by a high-level financial and strategic perspective. This decision increased the power of institutional investors and solidified the foundation for long-term investments. On the one hand, the participation of insurance companies contributes to the company's reducing operating costs (Zhao et al., 2021), the improvement of the corporate governance environment, and the stability of the market, and has a positive effect on the value of the company (Cornell et al., 2017; Olarewaju and Msomi, 2021). It can also effectively increase the company-specific information content in the stock price and improve market efficiency and stabilize the market. As a gray institutional investor, insurance companies prefer to invest in experience and pay more attention to the mechanism of corporate governance, which is more helpful in transferring risks and improving the overall operational efficiency (Ettlin et al., 2020; Guan and Hu, 2022). However, investors are irrational, and institutional investors are no exception (Zamri et al., 2017). Insurers may have a short-term vision, which in turn will influence managers to make short-term decisions that only increase short-term profits (Consuelo and Blanca, 2018). The media effects caused by information technology have an important impact on the development of the insurance industry (Kaigorodova et al., 2018). The question of how insurance funds boost market confidence, reduce share price risk, and stabilize financial markets when entering the market is very important. After the risk capital is increased, will it improve the efficiency of capital pricing through the company's governance supervision, stabilize investor sentiment, let them hold shares, and make correct investment judgments and reduce the same rise and fall effect in the market? Or will the information asymmetry effect prevail, so that investors' mood is quickly infected (Polonchek and Miller, 2005); and what if optimism or pessimism is amplified, resulting in an increase in the synchronicity of share prices? Given the important market position and influence of insurance companies, what role does insurance company participation play in regulating investor sentiment and share price synchronicity? The relationship has to be studied in greater depth.

The main contributions of this paper are as follows: first, from the point of view, there are still few studies on insurance company participation and stock price synchronicity, and the overall volume of research in the field is still relatively small. This paper offers a new perspective, examining insurance company participation, investor sentiment, and stock price synchronicity in a specific context. It is beneficial to thoroughly understand the relationship between investor sentiment and stock price synchronicity after the intervention of insurance companies, and provide suggestions on the investment behavior of institutional investors from insurance companies. Second, this paper enriches the impact of investor sentiment on share price synchronicity in the stock market forum under the background of internet finance and hopes to make marginal academic contributions. At the same time, the paper gives some practical advice for network risk management for emerging markets such as China, which helps to improve the efficiency of capital market pricing and promote the sustainable development of the market.

2 Literature review and hypothesis development

Share price synchronicity mainly refers to the relationship between a change in a company's share price and the overall

change of the market. Compared with a mature capital market, the "share price synchronicity" of an emerging capital market is more worthy of attention because, in the second case, the phenomenon of the "same rise and fall" is more pronounced. After examining data from a sample of more than 40 countries, Morck et al. (1999) found that Chinese capital markets have the second highest share price synchronicity in the world. In turn, Li and Myers (2006) found that Chinese share price synchronicity is very high in the world. Therefore, the issue of Chinese capital market share price synchronicity is very serious and it still demands the attention of researchers.

Factors determining stock price are complicated, and although there are many asset pricing models, none of them can provide a comprehensive explanation of the capital market stock price. This prompts researchers to study stock price synchronicity. Most researchers believe that stock price synchronicity is closely related to the efficiency of capital market information, which has a significant impact on a company's financial behavior, decision-making, and resource allocation. Stock price synchronicity has become an increasingly important focus of theoretical and practical research papers. Scholars explain synchronicity of stock prices from a perspective of "information efficiency" and "irrationality." One explanation of "information efficiency" is based on the view that the higher the company's characteristic information reflected in the stock price, the lower the synchronicity of the share price. Using data samples from more than 40 countries, Morck et al. (1999) found that a better property rights protection system has a positive effect on information trading behavior, and it improves the quality of stock price information and reduces share price synchronicity. Durnev et al. (2003) found that share price synchronicity was negatively correlated with share price information content. This view is further supported by the study of emerging market countries, which found that the level of the development of capital markets is negatively correlated with share price synchronicity (Li et al., 2004). The security analysis increased the synchronicity of stock prices because security analysts provide more market information (Chan and Hameed, 2006), and the quality of accounting information is positively correlated with share price synchronicity (Jin, Z., 2010). The more timely the company's accounting disclosure policy, the more transparent the information (Song, L., 2015), the more readable the annual report (Xuelian et al., 2018), the better the information environment for the company to improve governance, and the lower the share price synchronicity. The other method is to explain the synchronicity of stock prices from a perspective of "irrational factors." West (1988) argued that share price synchronicity measures market noise and the size of investor sentiment. Greenwood and Nathan (2007) confirmed that both investor sentiment and market friction affect synchronicity of stock prices. Kelly (2014) found that companies with lower share price synchronicity, less institutional investor holdings, and analyst analysis have less liquidity in stocks and higher transaction costs. It can be seen that the influence of irrational factors on stock price synchronicity is very significant, and this paper attempts to explain the synchronicity of stock price from this perspective.

In the capital market, attention of investors is a scarce resource (Kahneman, 1973), which leads the investors to analyze and judge the information they are concerned about due to insufficient time and energy, resulting in a deviation in value judgment and finally, stock price volatility. According to the theory of behavioral finance, investor sentiment is an important factor affecting stock price volatility (De Long et al., 1990). It is mainly reflected in the investors' beliefs and preferences, namely, rational expectations and rational preferences. "Belief" mainly refers to a deviation of investors' expectations about the future, while "preference" refers to different psychological expectations or personal preferences of the investors, namely, their preferences for individual stocks and risks. The "heterogeneous belief hypothesis" (Hong and Stein, 2003) argues that heterogeneous beliefs and pessimism of investors are also released into the market through intermediary channels.

In recent years, with the development of network finance, scholars began to choose proxy variables for investor sentiment for their research from stock bar forums. Das and Chen (2007) established an emotional index by examining bullish and bearish views of the stock market forum's users based on Morgan Stanley's high-tech stock index, and showed that the sentiment index had a strong correlation with market behavior. Posts from the online financial forums reflect investors' opinions because they contain information that affects stock returns and prices (Tumarkin, R., and Whitelaw, R. F., 2001). Antweiler, W. and Frank, M. Z. (2004) conducted a study of Yahoo e-mails and found that information contained in the stock messages helped to predict market volatility and that online stock message boards could drive the market, and the number of posts was positively correlated with the simultaneous fluctuations in stock prices. Especially since the beginning of the 21st century, the internet has become an important source of information for companies, and analysis of information from the internet is closely related to the extent to which investors understand a particular company (Amir and Eran, 2010). Social media websites have become a popular way for individuals to share their own results of financial security analysis. Message board sentiment is an important predictor of trading behavior (Sabherwal et al., 2011), as the views expressed in articles and comments predict future stock earnings and earnings surprises (Chen et al., 2014). Information posted on the investor's internet stock message board reflects an investment bias (Huang et al., 2016), which creates investor sentiment. In turn, investors determine the operations of the entire market through an insight into the target company (Ackert et al., 2016). Given information asymmetry, it became increasingly popular to disseminate information

online, and internet stock message boards have gradually become communicators of company-specific information, which can be incorporated into stock prices (Bowden et al., 2017; Li et al., 2018). Barberis et al. (1998) built a mood theory model for the rapid and convenient dissemination of information on the internet—the "anchoring" mentality of investors will lead to an insufficient response to stock price information, and widely available forum information may cause investors to overreact. Thus, investors' attention and emotions are characteristics of different stages of their investment behavior. According to the theory of cognitive psychology, the process of making an investment choice is actually an information processing process, which includes the stages of feeding input, making a judgment, transformation, processing, storage, and making a decision on a particular investment. At every stage of this process, there are cognitive biases which lead to errors in judgment, resulting in abnormal fluctuations in stock prices. Moreover, investors' attention to high-profile stocks does not necessarily mean that the bullish and bearish ideas of investors are the same. Therefore, it is necessary to study sentiments expressed in every particular post. The number of forum posts is used as a proxy variable for individual investors, and the content of the posts is used to extract personal information. As the number of posts increases, the stock is more likely to be noticed, leading to greater participation. Bullish and bearish views reflected in each post will form an emotional consistency index, which will lead to consistency of investor action. Subsequently, share price synchronicity will increase in the short term. On the other hand, if the number of posts on stocks decreases, stocks enter a state where nobody cares, investors' sentiment consistency index reduces, the stock market's same-up effect weakens, and synchronicity of stock prices decreases. Barber and Odean (2008) argued that most individual investors do not have enough energy to consider all of the available information and then make decisions, so they only consider information which attracts their attention. Therefore, the most popular stocks will have an upward price shock in the short term and then the effect will reverse. This reversal is consistent with over-focusing on weakness assumptions of limited attention (Seasholes and Wu, 2007); therefore, this paper considers the issue from a short-term perspective. Since most Chinese individual investors are not professionally trained, irrational behavior in the market is more pronounced—catching up with the kill is easier, investor sentiment is more consistent in the short term, and the same rise and fall phenomenon of stocks is more notable. Given the aforementioned factors, this paper puts forward the following hypothesis:

H1. Given that other conditions remain unchanged, the greater the number of stock market forum posts, the higher will be the sentiment consistency index and share price synchronicity in the short-term.

Development of the capital market cannot be separated from participation of institutional investors, including insurance companies. Specialized institutional investors have strong monitoring motivations due to large holdings of equity and long-term investment terms, which are beneficial for short-term institutional investors because they tend to trade rather than regulate. These findings suggest that institutional oversight limits managers' withdrawals to the company's cash flow. This reduces company-specific risks that managers absorb, resulting in a reduction in R^2 (An and Zhang, 2011). Therefore, insurance company participation contributes to the improvement of the corporate governance environment and stabilization of the market, and enhances the value of businesses (Cornell al., 2007). It can also effectively enhance the company's unique information content in the stock price and improve market efficiency. At the same time, as important institutional investors, insurance companies usually have professional analytical teams, access to more comprehensive information, and other advantages. They buy undervalued and premium stocks in order to achieve market balance, lower stock price volatility, and reduce stock price synchronicity. This is an important constraint on a surge and collapse of the "counterweight" (Statman, 1994). Contribution of insurance companies to economic growth is more evident in emerging markets (Han et al., 2010; Zhou et al., 2012). With regard to the extent to which insurance companies contribute to the overall risk impact of the market, corporate risk management affects investors' risk needs (Hitchcox et al., 2011). If the market is in good health, investors will certainly take the risk situation into account to make prudent investments, and investor sentiment will usually be more stable. In this case, the stock market will be the same, the group effect of "the same rise and fall" will be reduced, the capital market pricing efficiency will improve, and the simultaneous operation effect of stock prices will also be reduced.

However, internationalization of capital markets has led to increased competition for scarce equity capital—the basic idea describing investor relations is increasing the demand for own shares in competition with shareholders and other participants of financial markets (Hausele, 1998). As gray institutional investors, insurers prefer to invest in experience and emphasize mechanisms consistent with corporate governance, but investors are irrational and institutional investors are no exception (Zamri et al., 2017). Insurers may have a shorter vision, which would prompt managers to make short-term decisions which only increase short-term profits (Consuelo and Blanca, 2018). The media effect of information technology has a significant impact on the development of the insurance industry (Kaigorodova et al., 2018). Polonchek and Miller (2005) further confirmed the impact caused by information asymmetry in insurance companies. In the course of the investment-making process, information on their investment behavior is bound to spread across the internet, be

discussed in comments, and have an impact on investor sentiment. If it is good news, in times of high sentiment, the attitude of optimistic investors will influence the stock price, pushing up the real value of the stock and causing it to deviate from its normal value; the same up effect is serious: if it is bad news, the pessimistic investor's low mood will inevitably cause the stock price to deviate further from the normal value, which in turn will contribute to the decline effect (Zou and Sun, 2012). The impact of investor sentiment is bound to form a value error (Duan and Shou, 2006).

According to the theory of cognitive dissonance, in order to eliminate tension, individuals will increase cognition and change cognition, so as to achieve a new state of equilibrium. Therefore, what is the relationship between insurance company participation and share price synchronicity? What role does it play in affecting investor sentiment and share price synchronicity? The following hypotheses are put forward:

H2a. Insurance company participation reduces share price synchronicity and plays an intermediary role between investor sentiment and share price synchronicity.

H2b. Insurance company participation increases the synchronicity of stock prices and plays an intermediary role between investor sentiment and stock price synchronicity.

Compared with mature foreign markets, the most crucial characteristic of the majority of the listed Chinese companies is the background of state-owned enterprises. Given the unique property rights of state-owned enterprises, the companies have different orientations. Decision-making and actions of most state-owned enterprises are not based solely on pursuing economic interests but on maximizing national interests, ensuring economic development and social stability. As the largest shareholders, state-owned enterprises can lead to certain conflicts of interest and even constitute a threat to other shareholders. In turn, this results in information asymmetry problems and proxy conflicts. Major shareholders occupy funds for fulfilling their own objectives of carrying out particular transactions, which inevitably harms the interests of small- and medium-sized shareholders, leads to agent conflicts, and results in suboptimal resource allocation. The problem of agencies in state-owned enterprises is more prominent than in private enterprises, and the opportunistic behavior of managers has a greater impact on investor sentiment. When investor sentiment is high, it is more likely to cause a company to over-invest, which will lead to a new round of expansion for speculative motives. The high mood in the market makes investors think that greater future share price earnings are offsetting the risks and the hot talk on the stock bar forums is bound to attract more over-the-counter investors and capital. Given the increase in the number of posts and consistent strengthening of the investor sentiment index, the stock's co-rise-effect becomes more pronounced. In the process, company managers will deliberately conceal some of the negative news in order to cater to market sentiment, while a large number of posts on the hot theory and pessimism on the stock bar forum will lead to a decrease in the stock price (Tetlock, 2007; Ben-Rephael et al., 2012). In turn, the investor herd effect will result in a significant fall in share prices. Thus, the following hypothesis is put forward:

H3. Compared with the sample of private enterprises, the intermediary effect of risk-raising on investor sentiment and share price synchronicity is more evident in state-owned enterprises.

3 Data and methodology

3.1 Sample

This paper selects listed companies from the A-share market of Shanghai and Shenzhen in the period from 2007 to 2018 as research objects. The reason for the choice is due to the fact that new accounting standards have been implemented from 2007 onward, which deal with the following: 1) excluding financial listed companies, 2) excluding some companies marked with "ST" or "*ST," and 3) excluding some companies with missing data. To eliminate the effects of extreme values, all successive variables were processed at 5% by winsorizing, for a total of 6,839 observations. The financial data used were downloaded from the CSMAR database and cross-paired.

3.2 Model building and variable measurement

3.2.1 Variables measurement

1) Stock price synchronicity

Based on the research findings of Morck et al. (1999), Piotroski and Roulstone (2004), Gul et al. (2010), and Xu et al. (2013), this article will calculate stock price synchronicity as follows. First, the weekly return yield on the stock i:

$$R_{i,w,t} = \beta_0 + \beta_1 R_{M,w,t} + \beta_2 R_{M,w-1,t} + \beta_3 R_{I,w,t} + \beta_4 R_{I,w-1,t} + \varepsilon_{i,w,t}, \quad (1)$$

where R (i,w,t) represents the return on the stock i's consideration of cash dividend reinvestment of the t-week in the t-year; R (M, w, t) represents the weighted average return on market capitalization of the t-week in the t-year for all A-share companies; and R (I, w, t) on behalf of the weighted average return on the market value of other stocks in the same industry excluding stock i of the t-week in the t-year, where the industry classification is based on the SFC's 2012 industry classification criteria, and returns R^2, which represents the part where the share price can be explained by market fluctuations, 1-R^2 represents the characteristic risk of the company's price fluctuations. However, since the R^2 value range is within 0–1,

which brings risk to the actual estimate, R^2 is evaluated for the plurality, and we obtain the stock price synchronicity index of stock i in the t-year:

$$SYNCH_{(i,t)} = In\left(\left(R^2_{(i,t)}\right)/\left(1 - R^2_{(i,t)}\right)\right) \quad (2)$$

The higher the SYNCH, the higher the stock price synchronicity and the less accurate the company's individual stock information.

2) Derivation of investor sentiment indicators

The Oriental Fortune Internet Cafe and Sina Internet Cafe Forum are the most popular forums in China. Given the representativeness and availability of the data, referring to Antweiler and Frank (2004), Das and Chen (2007), and Tetlock et al. (2008), this paper chooses posts from the Oriental Wealth Internet Cafe and the Sina Internet Cafe Forum as the object of study. According to the tone of a post's content, it is considered either bullish or bearish. T_n stands for the total number of comments posted under a profile of a listed company within a year, and the variable represents investment concern. In order to facilitate calculation, natural arithmetic processing was carried out: TOPST = log (T_n).

SNCFMI stands for the indicator of the emotional consistency index, L_n represents the number of bullish posts, and D_n represents the number of bearish posts; the formula is:

$$SNCFMI = 1 - \sqrt{1 - \left(\frac{(L_n - D_n)}{T_n}\right)^2}. \quad (3)$$

3) Indicators of insurance company participation

The IP variable indicates whether there is insurance company participation in the stock, then the IP value equals 1, otherwise it equals 0; the SP variable indicates the percentage of insurance companies participating in shares.

4) Control variables

Following the literature (Chen et al., 2000; Zou & Sun, 2012), the following control variables are added: the average return of the stock in the current year (RET), the weekly yield standard deviation (SRET), the annual excess turnover rate (ETURN), the largest shareholding ratio (TOPHLD), the nature of the company's property rights (SN, if state-owned, defined as 1, otherwise defined as 0), the company's current year's market price-to-book ratio (P/B), asset–liability ratio (LEV), and the size of the company's assets (SIZE). At the same time, this paper also controls industry and annual variables; for detailed variable definitions, see Appendix A.

3.2.2 Research model

With reference to Gul et al. (2010), we intend to build the following models for testing, with the dependent variable being $SYNCH_{t+1}$ (stock price synchronicity) and the explanatory variables being $TOPST_t$, $SNCFMI_t$, IP_t, and SP_t:

$$SYNCH_{t+1} = \beta_0 + \beta_1 TOPST_t + controls + year + indu + \varepsilon, \quad (4)$$

$$SYNCH_{t+1} = \beta_0 + \beta_1 SNCFMI_t + controls + year + \mathrm{indu} + \varepsilon, \quad (5)$$

$$SYNCH_{t+1} = \beta_0 + \beta_1 TOPST_t + \beta_2 IP_t + \beta_3 IP_t \times TOPST_t + controls + year + indu + \varepsilon, \quad (6)$$

$$SYNCH_{t+1} = \beta_0 + \beta_1 TOPST_t + \beta_2 SP_t + \beta_3 SP_t \times TOPST_t + controls + year + indu + \varepsilon, \quad (7)$$

$$SYNCH_{t+1} = \beta_0 + \beta_1 SNCFMI_t + \beta_2 IP_t + \beta_3 IP_t \times SNCFMI_t + controls + year + indu + \varepsilon, \quad (8)$$

$$SYNCH_{t+1} = \beta_0 + \beta_1 SNCFMI_t + \beta_2 SP_t + \beta_3 SP_t \times SNCFMI_t + controls + year + indu + \varepsilon. \quad (9)$$

4 Results and discussion

4.1 Descriptive statistics

Table 1 is a descriptive statistic of the variables. The mean and standard deviation of share price synchronicity (SYNCH) is −0.8847 and 0.8794, respectively; the mean of the number index (TOPST) and sentiment consistency index (SNCFMI) is 0.8134 and 1.0016, respectively; and their standard deviations are 0.2268 and 0.0558, respectively, which is not very large, indicating that the investor sentiment indicators measured from different dimensions are relatively consistent. The standard deviation of whether insurance companies participate (IP) is 0.3029, and the maximum value of insurance companies' participation in equity (SP) is 1%, which indicates that the participation of insurance companies in shares is relatively uniform, but the proportion of participation is still relatively small. In addition, we perform median and interquartile tests on the main variables, which are generally consistent with the results of the main studies. The descriptive statistics of other variables are basically within a reasonable range.

TABLE 1 Descriptive statistics.

Statistic	Mean	St. Dev	Min	Max	Median	Pctl (25)	Pctl (75)
SYNCH	−0.8847	0.8794	−2.8500	1.0500	−0.7570	−1.2820	−0.4650
TOPST	0.8134	0.2268	−0.0231	1.6121	0.8546	0.0350	0.9860
SNCFMI	1.0016	0.0558	0.0200	1.2020	1.0009	0.0450	1.0130
SP	0.0008	0.0027	0.0000	0.0100	0.0006	0.0005	0.0080
IP	0.1022	0.3029	0.0000	1	0	0	0
SIZE	21.7515	0.9905	20.3300	24.0200	21.6190	20.9870	22.3020
LEV	0.3565	0.1767	0.0900	0.6900	0.3400	0.2060	0.4910
PB	3.8127	2.2166	0.0000	9.2200	3.2660	2.1550	4.9590
TOPHLD	0.3779	0.1446	0.1500	0.6500	0.3690	0.2610	0.4880
SN	0.8054	0.4004	0.0000	1	1	1	1
RET	0.0024	0.0092	−0.0100	0.0200	0.0004	−0.004	0.0080
SRET	0.0573	0.0342	0.0000	0.1400	0.0530	0.0400	0.0710
ETURN	0.1415	0.5438	0.0570	1.6700	0.1350	−0.1150	0.9520

TABLE 2 Regression test results for hypotheses 1 and 2.

	$SYNCH_{t+1}$					
	(1)	(2)	(3)	(4)	(5)	(6)
$TOPST_t$	0.084 *** (16.58)	0.075 *** (13.92)	0.063 *** (11.88)			
$SNCFMI_t$	—	0.061 * (3.13)	—	—	0.057 * (2.8)	0.039* (1.92)
IP_t	—	—	−0.092 *** (−3.92)	−0.173* (−8.50)		
SP_t	—	—	—	−16.31 *** (−6.34)	−4.075* (−200.15)	
$TOPST_t\_IP_t$	—	−0.031 * (−1.52)	—	—		
$TOPST_t\_SP_t$	—	—	−9.169 *** (−2.73)			
$SNCFMI_t\_IP_t$	—	—	—	−0.101* (−4.96)		
$SNCFMI_t\_SP_t$	—	—	—	—	−14.13* (−694.01)	
$ETURN_t$	−0.045 *** (−9.84)	−0.044 *** (−9.66)	−0.045 *** (−10.00)	−0.046 *** (−10.13)	−0.044 *** (−9.83)	−0.045 *** (−9.99)
LEV_t	0.065 *** (4.70)	0.067 *** (4.81)	0.056 *** (4.05)	0.059 *** (4.23)	0.057 *** (4.11)	0.060 *** (4.31)
P/B_t	−0.008 *** (−6.76)	−0.007 *** (−6.22)	−0.008 *** (−6.54)	−0.008 *** (−6.60)	−0.007 *** (−6.05)	−0.007 *** (−6.18)
RET_t	0.795 ** (2.49)	0.744 ** (2.33)	0.688 ** (2.15)	0.704 ** (2.20)	0.638 ** (1.99)	0.655 ** (2.05)
$SIZE_t$	0.016 *** (5.52)	0.018 *** (6.07)	0.021 *** (6.99)	0.020 *** (6.80)	0.022 *** (7.58)	0.021 *** (7.34)
SN_t	−0.027 *** (−4.78)	−0.030 *** (−5.30)	−0.028 *** (−4.90)	−0.028 *** (−4.89)	−0.031 *** (−5.41)	−0.030 *** (−5.36)
$SRET_t$	−0.122 (−1.46)	−0.132 (−1.58)	−0.138 * (−1.66)	−0.127 (−1.52)	−0.149 * (−1.79)	−0.135 (−1.62)
$TOPHLD_t$	0.009 (0.59)	0.004 (0.24)	0.012 (0.79)	0.009 (0.57)	0.007 (0.47)	0.003 (0.23)
_cons	−0.396 *** (−5.92)	−0.314 *** (−3.97)	−0.472 *** (−7.00)	−0.456 *** (−6.79)	−0.401 *** (−4.97)	−0.407 *** (−5.09)
Industry	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
N	6,839	6,839	6,839	6,839	6,839	6,839
Adj_R^2	0.0537	0.05328	0.05416	0.055	0.05384	0.05424

Note: The following brackets are standard errors below the coefficients, which represent significant values at the 10%, 5%, and 1% levels, respectively.

4.2 Analysis of main empirical results

Table 2 shows the regression test results of hypotheses 1 and 2; the empirical results are all controlled for the annual and industry variables because the variables are the share price synchronization "$SYNCH_{t+1}$." Column (1) and column (2) examin the impact of investor sentiment indicators represented by the number of posts and sentiment consistency

indices on the synchronicity of stock prices, in which the coefficients of $TOPST_t$ and $SNCFMI_t$ were positive and significant at the level of 1% and 10%, respectively, indicating that investor sentiment and share price synchronicity were positive. The greater the volatility of investor sentiment, the greater the synchronicity of share prices. This is mainly because when good news appears in the market, the number of posts in the stock bar forum increases, and the higher the sentiment consistency index, the higher the investor sentiment. Thus, market sentiment helped increase the psychological expectations of investors, prompting its behavior on the "herd effect"; where it is proactive to buy stocks, the stock price is on the upward trend; at the same time, it sends a signal to other investors in the market that they think that the stock price continues to increase, thus entering the market to buy a large number of stocks; when the "same-up effect" of the stock is very serious, the stock price increases to a certain extent, the stock is overvalued, and it will create a bubble; then, the stock price starts to show a downward trend. In particular, when bad news starts flowing into the market, the market becomes relatively depressed, and investors rush to sell their stocks in order to avoid the continuous fall of stock price caused by the depreciation of funds. The more the stock price falls, the more investors follow each other, and market pessimism continues to increase until the point when the investors try to get rid of these stocks and sell them as fast as possible. The stock price will fall "severely." So, the investor sentiment of the stock market forum increased the synchronicity of the share price, verifying hypothesis H1.

Columns (3)–(6) test the results of the relationship between insurance company participation, investor sentiment, and share price synchronicity. Among them, the coefficients of $TOPST_t$ are positive and both are significant at the 1% significance level, the coefficients of $SNCFMI_t$ are positive and both are significant at the 10% significance level, the coefficients of IP_t and SP_t are negative and significant at the 1% and 10% significance levels, respectively, and the coefficients of $TOPST_t\_IP_t$ (the interaction term of $TOPST_t$ and IP_t) and $TOPST_t\_SP_t$ (the interaction of $TOPST_t$ and SP_t) are negative and significant at 10% and 1%, respectively. The coefficients of $SNCFMI_t\_IP_t$ (the interaction term of $SNCFMI_t$ and IP_t) and $SNCFMI_t\_SP_t$ (the interaction term of $SNCFMI_t$.and SP_t) are negative and both are significant at the 10% significance level. This shows that although investor sentiment has increased the synchronicity of stock prices, the risk of insurance company participation effectively reduces the impact of investor sentiment to share price synchronicity, which played a certain intermediary effect. This may be because insurance company participation has played a role in reducing the synchronicity of stock prices through the adjustment of investor sentiment; because insurance companies' participation in the market is a positive signal, investors have a higher degree of psychological security, the number of posts indicate that the market is a hot topic on the internet, and the stock has investment opportunities temporarily, and the market will have a large influx of funds, which is good news. Investors have good expectations of the stock price and a higher sentiment consistency index; they will firmly hold stocks and the market situation will be stable. The higher the proportion of insurance company shareholdings, the more stable the investor sentiment; they will feel that this is good news in the capital market and have a good value judgment, they will not be in a hurry to leave the market and investors' herd effect is weaker, and the stock's same rise and fall effect and the stock price synchronicity is lower, which verifies hypothesis H2a.

Table 3 shows the regression result of the sample of private enterprises and state-owned enterprises in testing insurance company participation, investor sentiment, and stock price synchronicity, and the empirical results all control the annual and industry variables, as the explained variables are share price synchronization "$SYNCH_{t+1}$." In columns (5)–(8), the coefficients of $TOPST_t$ were positive and significant at the 1% significance level, the coefficients of $SNCFMI_t$ were positive and both were significant at the 1% and 5% levels, the coefficients of IP_t and SP_t were negative and significant at the significance levels of 1% and 10%, respectively, and the $TOPST_t\_IP_t$ (the interaction of $TOPST_t$ and IP_t) and TOPSTt_SPt ($TOPST_t$ and SP_t interactions) are both negative and significant at the 1% significance level. The coefficients of $SNCFMI_t\_IP_t$ (the interaction of $SNCFMI_t$ and IP_t) and $SNCFMI_t\_SP_t$ (the interaction of $SNCFMI_t$ and SP_t) were negative and significant at the significance level of 1% and 10%, respectively. In general, the coefficients of the state-owned sample of columns (5)–(8) were more significant than the private sample of columns (1)–(4). This may be because the so-called enterprise sample is more serious than private enterprises because of the problem of proxy conflict; the management's profit-scenting behavior will have a greater impact on the mood of investors through the network posts, especially on the mainstream views in the posts, where emotional resonance and consensus view are very easy to produce a "herd effect," and the effect of the same rise and fall of share price is stronger. The insurance company participation can reduce the share price synchronicity through the intermediary effect on investor sentiment because insurance participation means the influx of funds in the market; first of all, it can enhance market confidence, and investors expect good future returns of the stock price and they will be at ease holding shares; however, when the market situation is relatively stable, investor sentiment will be more stable with higher proportion of insurance company shareholdings. This is good news for the capital market, as investors will not be in a hurry to leave the market and will insist on investment value. Therefore, the impact of insurance company participation on state-owned enterprises is more significant than that of private enterprises and hypothesis H3 is verified.

TABLE 3 Regression result of the split sample of private enterprises and state-owned enterprises.

	$SYNCH_{t+1}$							
	Private enterprises				**State-owned enterprises**			
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
$TOPST_t$	0.098 *** (7.25)	0.065 *** (4.99)		—	0.065 *** (10.96)	0.058 *** (9.85)		—
$SNCFMI_t$	—	—	−0.034 (−0.63)	−0.019 (−0.36)	—	0.112 *** (4.94)	0.096 ** (4.26)	
IP_t	0.040 (0.79)		−0.292 (−1.06)		−0.167 *** (−6.20)		−0.149 * (−0.02)	
SP_t	—	−1.408 (−0.24)		−5.442 (−0.17)		−23.00 *** (−7.88)		−1.831* (−0.25)
$TOPST_t\_IP_t$	0.082 (0.53)		—	—	−0.141 *** (−4.05)		—	—
$TOPST_t\_SP_t$		−11.89 (−0.69)	—	—	—	−18.643 *** (−4.81)		—
$SNCFMI_t\_IP_t$		—	0.173 (0.63)		—	—	−0.196 *** (−3.22)	
$SNCFMI_t\_SP_t$		—	—	−7.006 (−0.21)		—	—	−13.96 * (−1.92)
$ETURN_t$	−0.082 *** (−7.15)	−0.082 *** (−7.16)	−0.082 *** (−7.13)	−0.082 *** (−7.12)	−0.035 *** (−7.02)	−0.036 *** (−7.14)	−0.034 *** (−6.79)	−0.035 *** (−6.96)
LEV_t	−0.253 *** (−7.88)	−0.236 *** (−7.34)	−0.252 *** (−7.83)	−0.236 *** (−7.33)	0.153 *** (9.63)	0.151 *** (9.53)	0.155 *** (9.80)	0.154 *** (9.68)
P/B_t	−0.027 *** (−8.49)	−0.028 *** (−8.69)	−0.026 *** (−8.26)	−0.027 *** (−8.52)	−0.007 *** (−5.34)	−0.007 *** (−5.27)	−0.006 *** (−4.96)	−0.006 *** (−4.94)
RET_t	−0.686 (−0.85)	−0.557 (−0.69)	−0.699 (−0.86)	−0.569 (−0.70)	0.542 (1.53)	0.531 (1.50)	0.477 (1.35)	0.468 (1.32)
$SIZE_t$	0.058 *** (9.72)	0.052 *** (8.86)	0.060 *** (10.06)	0.054 *** (9.17)	−0.003 (−0.79)	−0.002 (−0.58)	−0.002 (−0.43)	−0.001 (−0.23)
SN_t	−1.039 *** (−7.72)	−0.900 *** (−6.78)	−0.980 *** (−5.50)	−0.873 *** (−5.03)	−0.038 (−0.99)	−0.046 (−1.19)	0.022 (0.49)	0.005 (0.11)
$SRET_t$	0.910 *** (3.99)	0.933 *** (4.09)	0.898 *** (3.93)	0.920 *** (4.03)	−0.383 *** (−4.22)	−0.372 *** (−4.10)	−0.395 *** (−4.35)	−0.378 *** (−4.17)
$TOPHLD_t$	−0.177 *** (−4.76)	−0.189 *** (−5.09)	−0.182 *** (−4.90)	−0.190 *** (−5.13)	0.038 ** (2.21)	0.037 ** (2.14)	0.034 ** (1.96)	0.032 * (1.88)
_cons	0.001* (0.001)	0.003* (0.000.)	0.013 *** (0.001)	0.012 *** (0.002)	0.003 *** (0.000)	0.003*** (0.000)	0.001 *** (0.000)	0.011 *** (0.002)
Industry	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES
N	1,334	1,334	1,334	1,334	5,283	5,283	5,283	5,283
Adj_R^2	0.05463	0.05509	0.05421	0.05468	0.08541	0.08495	0.08496	0.08474

Note: The following brackets are standard errors below the coefficients, which represent significant values at the 10%, 5%, and 1% levels, respectively.

Through the aforementioned analysis, the basic assumptions have been verified, but there are still some points that need further explanation. With regard to whether the impact of investors' positive and negative emotions on the synchronization of stock prices is symmetrical, from the efficient market hypothesis, the behavior of investors in the market is incorporated as information in the share price, but this hypothesis is valid if the market subject is rational and transmits valid private information. This hypothesis is based on the assumption that market participants are not fully rational and that investor sentiment represents different attitudes to investing in the market. However, from the theory of behavioral finance, every market player is a behavioral financier whose behavior is not fully qualified and does not follow a set paradigm, and is more influenced by the psychological and market environment. Therefore, in different market environments where investor sentiment is optimistic and pessimistic, the impact of positive insurance intervention on investors is not entirely symmetrical

TABLE 4 Robustness test.

	SYNCHt+1			SYNCH2t+1		
	(1)	(2)	(3)	(4)	(5)	(6)
$TOPST_t$	—	—	0.044 *** (8.18)	0.034 *** (6.39)		—
$SNCFMI_t$	—	—	—	—	0.110 *** (5.38)	0.122 *** (6.07)
IP_t	−0.060 *** (−6.77)		−0.129 *** (−5.47)		−0.082 (−0.61)	
SP_t	—	−9.256 *** (−9.63)		−20.35 *** (−7.83)		−7.880 (−0.52)
$TOPST_t\_IP_t$	—	—	−0.087 *** (−2.94)		—	—
$TOPST_t\_SP_t$	—	—	—	−15.513 *** (−4.58)		—
$SNCFMI_t\_IP_t$	—	—	—	—	−0.015 (−0.12)	
$SNCFMI_t\_SP_t$	—	—	—	—	—	−17.19 (−1.14)
$SENTB_t$	0.068 *** (29.47)	0.070 *** (30.44)		—	—	—
$SENTB_t\_IP_t$	−0.031 ** (−2.18)		—	—	—	—
$SENTB_t\_SP_t$	—	−2.445 (−1.56)		—	—	—
$ETURN_t$	−0.048 *** (−10.68)	−0.049 *** (−10.83)	−0.027 *** (−5.84)	−0.027 *** (−5.95)	−0.026 *** (−5.76)	−0.027 *** (−5.90)
LEV_t	0.066 *** (4.72)	0.069 *** (4.94)	0.095 *** (6.78)	0.097 *** (6.93)	0.094 *** (6.67)	0.096 *** (6.85)
P/B_t	−0.007 *** (−6.12)	−0.007 *** (−6.27)	−0.004 *** (−3.01)	−0.004 *** (−3.04)	−0.003 *** (−2.58)	−0.003 *** (−2.70)
RET_t	1.097 *** (3.42)	1.116 *** (3.48)	0.342 (1.06)	0.354 (1.10)	0.342 (1.06)	0.357 (1.11)
$SIZE_t$	0.018 *** (6.22)	0.017 *** (5.96)	0.022 *** (7.38)	0.021 *** (7.26)	0.024 *** (8.01)	0.023 *** (7.80)
SN_t	−0.031 *** (−5.41)	−0.031 *** (−5.38)	−0.029 *** (−5.06)	−0.029 *** (−5.06)	−0.031 *** (−5.47)	−0.031 *** (−5.42)
$SRET_t$	−0.202 ** (−2.42)	−0.187 ** (−2.24)	−0.435 *** (−5.15)	−0.425 *** (−5.05)	−0.447 *** (−5.30)	−0.433 *** (−5.14)
$TOPHLD_t$	0.012 (0.80)	0.008 (0.55)	0.032 ** (2.10)	0.030 * (1.93)	0.027 * (1.76)	0.024 (1.54)
_cons	−0.343 *** (−5.06)	−0.329 *** (−4.88)	−0.504 *** (−7.40)	−0.492 *** (−7.27)	−0.625 *** (−7.67)	−0.626 *** (−7.75)
Industry	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
N	6,839	6,839	6,839	6,839	6,839	6,839
Adj_R2	0.05532	0.05571	0.05192	0.05229	0.05177	0.05211

Note: The following brackets are standard errors below the coefficients, which represent significant values at the 10%, 5%, and 1% levels, respectively.

and does not have the same effect of reducing share price synchronization.

In addition, different types of insurance companies have different investment strategies; there is a big difference between life insurance companies and non-life insurance companies. In terms of product attributes, life insurance mainly covers people in old age and sickness, while non-life insurance mainly covers people for property losses. However, most consumers are accustomed to thinking of non-life insurance as consumption and life insurance products as investment with the function of preserving and increasing value. From the perspective of the public body of the market, people generally prefer to save money rather than spend it, and thus, people are more inclined in practice to buy life insurance products from banks rather than general insurance products. Therefore, in terms of relative strength, life insurance term business has a large cash flow and wholesale business has a stable cash flow, while non-life insurance has greater uncertainty. From the perspective of cooperative interests, life insurance companies are more complementary in terms of business, generally larger in scale, with strong going concern, good corporate credit, and sound corporate governance, while non-life insurance companies are relatively small, with brutal

TABLE 5 Regression result of the PSM model.

	$SYNCH_{t+1}$			
	(1)	(2)	(3)	(4)
$TOPST_t$	0.004* (0.20)	0.058 ** (4.06)		—
$SNCFMI_t$	—	—	0.052* (2.6)	0.077* (3.85)
IP_t	−0.193 *** (−5.76)		−0.078* (−3.90)	
SP_t	—	−30.29 *** (−8.93)		−21.456 *** (−6.32)
$TOPST_t\_IP_t$	−0.133 *** (−3.21)		—	—
$TOPST_t\_SP_t$		−24.618 *** (−5.74)		—
$SNCFMI_t\_IP_t$		—	−0.170* (−8.50)	
$SNCFMI_t\_SP_t$		—	—	−33.29* (−1.76)
$ETURN_t$	−0.098 *** (−9.53)	−0.101 *** (−9.88)	−0.096 *** (−9.40)	−0.101 *** (−9.83)
LEV_t	−0.182 *** (−5.63)	−0.170 *** (−5.28)	−0.182 *** (−5.64)	−0.167 *** (−5.18)
P/B_t	0.002 (0.51)	0.001 (0.48)	0.002 (0.68)	0.001 (0.44)
RET_t	2.617 *** (3.39)	2.855 *** (3.70)	2.513 *** (3.26)	2.790 *** (3.62)
$SIZE_t$	0.151 *** (22.66)	0.147 *** (22.02)	0.154 *** (23.11)	0.148 *** (22.16)
SN_t	0.052 *** (4.06)	0.050 *** (3.90)	0.049 *** (3.85)	0.048 *** (3.80)
$SRET_t$	2.022 *** (10.11)	2.120 *** (10.61)	1.993 *** (9.97)	2.120 *** (10.60)
$TOPHLD_t$	−0.204 *** (−5.88)	−0.217 *** (−6.22)	−0.210 *** (−6.03)	−0.227 *** (−6.54)
_cons	−3.103 *** (−19.91)	−2.997 *** (−19.25)	−3.204 *** (−15.48)	−3.122 *** (−15.75)
Industry	YES	YES	YES	YES
Year	YES	YES	YES	YES
N	1,381	1,381	1,381	1,381
Adj_R^2	0.06284	0.06466	0.06231	0.06378

Note: The following brackets are standard errors below the coefficients, which represent significant values at the 10%, 5%, and 1% levels, respectively.

competition, high volatility, and unstable cash flows prone to default, and for this reason, financial institutions have relatively less trust in them. As a result, life insurance funding is relatively large, has low claim risk and is trusted by the financial markets, and its impact on the market is relatively high. Therefore, life insurance funds have a relatively stronger impact on the market.

4.3 Endogenous problems

Reverse causality (also known as co-factoring bias), missing variables, and measurement bias (Fazzari et al., 1988) are the main sources of endogenous problems. As far as reverse causality is concerned, since the first-order lag of the interpreted variable is used to regress in this paper, it weakens the possible endogenous problem to some extent. These variables may indirectly affect share price synchronicity. Measurement bias is always present in social survey data; considering that the survey data used in this paper have strict data quality control, this paper believes that the endogenous impact is limited.

At the same time, the robust analysis part of this paper also carried out PSM analysis to solve the problem of sample selection deviation, further weakening the endogenous problem.

5. Robustness test

Table 4 shows the result of the robustness test. Columns (1) and (2) change the arguments SENTB, SENTB is bullish index B, which is calculated as $\ln((1 + L_n)/(1 + D_n))$; columns (3)– (6) replace "$SYNCH_{t+1}$" with "$SYNCH2_{t+1}$," $SYNCH2_{t+1}$ is recalculated on the basis of the SFC's 2002 industry classification standard, and then the regression test is carried out separately; the regression results are consistent, and H1 and H2a are further verified.

In order to prevent the endogenous problems caused by the systematic differentiation between investor sentiment index companies and non-investor sentiment index companies, this paper uses the PSM method to select a matching sample for companies with investor sentiment through the ratio tendency score (PS); the relationship between insurance company participation, investor sentiment, and stock price synchronization is tested, and the excess turnover rate of individual stock (ETURN), asset–liability rate (LEV), price-to-book ratio (P/B), weekly mean earnings of stock (RET), company size (SIZE), property nature (SN), standard deviation of RET (SRET), and the largest shareholder shareholding ratio (TOPHLD), the eight aforementioned company characteristic

TABLE 6 Description of statistics before and after PSM pairing.

		TOPST						SNCFMI					
		Unmatched sample			Matched sample			Unmatched sample			Matched sample		
		≤0.8089	>0.8089	Proportion (%)	≤0.8089	>0.8089	Proportion (%)	≤1.0025	>1.0025	Proportion (%)	≤1.0025	>1.0025	Proportion (%)
SP	≤0.0008	3,070	3,218	48.82	390	441	46.93	3,718	2,570	59.13	435	396	52.35
	>0.0008	387	165	70.11	386	165	70.05	322	230	58.33	322	229	58.44
TOPHLD	≤0.3779	1,697	1,791	48.65	323	261	55.31	2,166	1,322	62.10	353	231	60.45
	>0.3779	1,760	1,592	52.51	453	345	56.77	1,874	1,478	55.91	404	394	50.63
ETURN	≤0.1415	2,444	2,674	47.75	563	479	54.03	3,122	1,996	61.00	595	447	57.10
	>0.1415	1,013	709	58.83	213	127	62.65	918	804	53.31	162	178	47.65
LEV	≤0.3565	1935	1,654	53.91	448	263	63.01	2,111	1,478	58.82	373	338	52.46
	>0.3565	1,522	1,729	46.82	328	343	48.88	1,929	1,322	59.34	384	287	57.23
SIZE	≤21.7515	2,152	1,681	56.14	398	199	66.67	2,138	1,695	55.78	302	295	50.59
	>21.7515	1,305	1702	43.40	378	407	48.15	1,902	1,105	63.25	455	330	57.96

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TABLE 7 Marginal effect analysis of $SYNCH_{t+1}$ in the PSM sample.

TOPST1	Sp1	SIZE1	TOPHLD1	LEV1	Estimate	Standard error	Alpha	Lower	Upper	Wald chi-square	Pr > ChiSq
≤0.8089	≤0.0008	≤21.7515	≤0.3779	≤0.3565	−0.92335	0.061293	0.05	−1.04348	−0.80322	226.941	<0.0001
≤0.8089	≤0.0008	≤21.7515	≤0.3779	>0.3565	−0.89045	0.072836	0.05	−1.03321	−0.7477	149.462	<0.0001
≤0.8089	≤0.0008	≤21.7515	>0.3779	≤0.3565	−0.9273	0.059799	0.05	−1.0445	−0.81009	240.465	<0.0001
≤0.8089	≤0.0008	≤21.7515	>0.3779	>0.3565	−0.8944	0.069398	0.05	−1.03042	−0.75838	166.101	<0.0001
≤0.8089	≤0.0008	>21.7515	≤0.3779	≤0.3565	−0.80456	0.066832	0.05	−0.93555	−0.67358	144.927	<0.0001
≤0.8089	≤0.0008	>21.7515	≤0.3779	>0.3565	−0.77167	0.064718	0.05	−0.89851	−0.64482	142.171	<0.0001
≤0.8089	≤0.0008	>21.7515	>0.3779	≤0.3565	−0.80851	0.061972	0.05	−0.92997	−0.68705	170.207	<0.0001
≤0.8089	≤0.0008	>21.7515	>0.3779	>0.3565	−0.77561	0.057046	0.05	−0.88742	−0.6638	184.857	<0.0001
≤0.8089	>0.0008	≤21.7515	≤0.3779	≤0.3565	−1.04677	0.058809	0.05	−1.16203	−0.9315	316.82	<0.0001
≤0.8089	>0.0008	≤21.7515	≤0.3779	>0.3565	−1.01387	0.069444	0.05	−1.14998	−0.87776	213.155	<0.0001
≤0.8089	>0.0008	≤21.7515	>0.3779	≤0.3565	−1.05071	0.059713	0.05	−1.16775	−0.93368	309.617	<0.0001
≤0.8089	>0.0008	≤21.7515	>0.3779	>0.3565	−1.01782	0.067982	0.05	−1.15106	−0.88457	224.157	<0.0001
≤0.8089	>0.0008	>21.7515	≤0.3779	≤0.3565	−0.92798	0.06625	0.05	−1.05783	−0.79813	196.205	<0.0001
≤0.8089	>0.0008	>21.7515	≤0.3779	>0.3565	−0.89509	0.062663	0.05	−1.0179	−0.77227	204.038	<0.0001
≤0.8089	>0.0008	>21.7515	>0.3779	≤0.3565	−0.93193	0.063649	0.05	−1.05668	−0.80718	214.381	<0.0001
≤0.8089	>0.0008	>21.7515	>0.3779	>0.3565	−0.89903	0.057276	0.05	−1.01129	−0.78677	246.377	<0.0001
>0.8089	≤0.0008	≤21.7515	≤0.3779	≤0.3565	−0.95442	0.061802	0.05	−1.07555	−0.83329	238.492	<0.0001
>0.8089	≤0.0008	≤21.7515	≤0.3779	>0.3565	−0.92153	0.070468	0.05	−1.05964	−0.78341	171.014	<0.0001
>0.8089	≤0.0008	≤21.7515	>0.3779	≤0.3565	−0.95837	0.061331	0.05	−1.07858	−0.83816	244.174	<0.0001
>0.8089	≤0.0008	≤21.7515	>0.3779	>0.3565	−0.92547	0.067821	0.05	−1.0584	−0.79255	186.21	<0.0001
>0.8089	≤0.0008	>21.7515	≤0.3779	≤0.3565	−0.83564	0.065014	0.05	−0.96306	−0.70821	165.206	<0.0001
>0.8089	≤0.0008	>21.7515	≤0.3779	>0.3565	−0.80274	0.059553	0.05	−0.91946	−0.68602	181.693	<0.0001
>0.8089	≤0.0008	>21.7515	>0.3779	≤0.3565	−0.83958	0.061022	0.05	−0.95918	−0.71998	189.299	<0.0001
>0.8089	≤0.0008	>21.7515	>0.3779	>0.3565	−0.80669	0.052301	0.05	−0.90919	−0.70418	237.894	<0.0001
>0.8089	>0.0008	≤21.7515	≤0.3779	≤0.3565	−1.07784	0.070704	0.05	−1.21642	−0.93926	232.391	<0.0001
>0.8089	>0.0008	≤21.7515	≤0.3779	>0.3565	−1.04494	0.077208	0.05	−1.19627	−0.89362	183.175	<0.0001
>0.8089	>0.0008	≤21.7515	>0.3779	≤0.3565	−1.08179	0.072313	0.05	−1.22352	−0.94005	223.792	<0.0001
>0.8089	>0.0008	≤21.7515	>0.3779	>0.3565	−1.04889	0.076701	0.05	−1.19922	−0.89856	187.007	<0.0001
>0.8089	>0.0008	>21.7515	≤0.3779	≤0.3565	−0.95905	0.075014	0.05	−1.10608	−0.81203	163.454	<0.0001
>0.8089	>0.0008	>21.7515	≤0.3779	>0.3565	−0.92616	0.069012	0.05	−1.06142	−0.7909	180.102	<0.0001
>0.8089	>0.0008	>21.7515	>0.3779	≤0.3565	−0.963	0.073568	0.05	−1.10719	−0.81881	171.347	<0.0001
>0.8089	>0.0008	>21.7515	>0.3779	>0.3565	−0.9301	0.065112	0.05	−1.05772	−0.80249	204.05	<0.0001
SNCFMI1	Sp1	SIZE1	TOPHLD1	LEV1	Estimate	Standard Error	Alpha	Lower	Upper	Wald Chi-Square	Pr > ChiSq
≤1.0025	≤0.0008	≤21.7515	≤0.3779	≤0.3565	−0.9295	0.059735	0.05	−1.04658	−0.81243	242.128	<0.0001
≤1.0025	≤0.0008	≤21.7515	≤0.3779	>0.3565	−0.89896	0.069892	0.05	−1.03594	−0.76197	165.436	<0.0001
≤1.0025	≤0.0008	≤21.7515	>0.3779	≤0.3565	−0.93162	0.059875	0.05	−1.04897	−0.81426	242.093	<0.0001
≤1.0025	≤0.0008	≤21.7515	>0.3779	>0.3565	−0.90107	0.067817	0.05	−1.03399	−0.76815	176.538	<0.0001
≤1.0025	≤0.0008	>21.7515	≤0.3779	≤0.3565	−0.81204	0.064473	0.05	−0.9384	−0.68567	158.635	<0.0001
≤1.0025	≤0.0008	>21.7515	≤0.3779	>0.3565	−0.78149	0.060207	0.05	−0.8995	−0.66349	168.482	<0.0001
≤1.0025	≤0.0008	>21.7515	>0.3779	≤0.3565	−0.81415	0.061149	0.05	−0.934	−0.6943	177.27	<0.0001
≤1.0025	≤0.0008	>21.7515	>0.3779	>0.3565	−0.78361	0.053897	0.05	−0.88924	−0.67797	211.377	<0.0001
≤1.0025	>0.0008	≤21.7515	≤0.3779	≤0.3565	−1.04564	0.06111	0.05	−1.16541	−0.92586	292.78	<0.0001
≤1.0025	>0.0008	≤21.7515	≤0.3779	>0.3565	−1.01509	0.070504	0.05	−1.15328	−0.87691	207.29	<0.0001
≤1.0025	>0.0008	≤21.7515	>0.3779	≤0.3565	−1.04775	0.063234	0.05	−1.17169	−0.92381	274.547	<0.0001
≤1.0025	>0.0008	≤21.7515	>0.3779	>0.3565	−1.0172	0.070232	0.05	−1.15486	−0.87955	209.77	<0.0001

(Continued on following page)

TABLE 7 (*Continued*) Marginal effect analysis of $SYNCH_{t+1}$ in the PSM sample.

TOPST1	Sp1	SIZE1	TOPHLD1	LEV1	Estimate	Standard error	Alpha	Lower	Upper	Wald chi-square	Pr > ChiSq
≤1.0025	>0.0008	>21.7515	≤0.3779	≤0.3565	−0.92817	0.067959	0.05	−1.06137	−0.79497	186.533	<0.0001
≤1.0025	>0.0008	>21.7515	≤0.3779	>0.3565	−0.89762	0.063297	0.05	−1.02169	−0.77356	201.102	<0.0001
≤1.0025	>0.0008	>21.7515	>0.3779	≤0.3565	−0.93028	0.066695	0.05	−1.061	−0.79956	194.553	<0.0001
≤1.0025	>0.0008	>21.7515	>0.3779	>0.3565	−0.89974	0.059447	0.05	−1.01625	−0.78322	229.071	<0.0001
>1.0025	≤0.0008	≤21.7515	≤0.3779	≤0.3565	−0.95061	0.062919	0.05	−1.07393	−0.82729	228.262	<0.0001
>1.0025	≤0.0008	≤21.7515	≤0.3779	>0.3565	−0.92006	0.072976	0.05	−1.06309	−0.77703	158.955	<0.0001
>1.0025	≤0.0008	≤21.7515	>0.3779	≤0.3565	−0.95272	0.060592	0.05	−1.07148	−0.83396	247.229	<0.0001
>1.0025	≤0.0008	≤21.7515	>0.3779	>0.3565	−0.92217	0.068816	0.05	−1.05705	−0.7873	179.575	<0.0001
>1.0025	≤0.0008	>21.7515	≤0.3779	≤0.3565	−0.83314	0.066844	0.05	−0.96415	−0.70213	155.349	<0.0001
>1.0025	≤0.0008	>21.7515	≤0.3779	>0.3565	−0.80259	0.063138	0.05	−0.92634	−0.67885	161.588	<0.0001
>1.0025	≤0.0008	>21.7515	>0.3779	≤0.3565	−0.83525	0.061208	0.05	−0.95522	−0.71529	186.219	<0.0001
>1.0025	≤0.0008	>21.7515	>0.3779	>0.3565	−0.80471	0.054427	0.05	−0.91138	−0.69803	218.602	<0.0001
>1.0025	>0.0008	≤21.7515	≤0.3779	≤0.3565	−1.06674	0.065528	0.05	−1.19517	−0.93831	265.013	<0.0001
>1.0025	>0.0008	≤21.7515	≤0.3779	>0.3565	−1.03619	0.074702	0.05	−1.18261	−0.88978	192.404	<0.0001
>1.0025	>0.0008	≤21.7515	>0.3779	≤0.3565	−1.06885	0.065221	0.05	1.19668	−0.94102	268.571	<0.0001
>1.0025	>0.0008	≤21.7515	>0.3779	>0.3565	−1.03831	0.072374	0.05	−1.18016	−0.89646	205.821	<0.0001
>1.0025	>0.0008	>21.7515	≤0.3779	≤0.3565	−0.94927	0.071406	0.05	−1.08922	−0.80932	176.731	<0.0001
>1.0025	>0.0008	>21.7515	≤0.3779	>0.3565	−0.91873	0.067357	0.05	−1.05074	−0.78671	186.039	<0.0001
>1.0025	>0.0008	>21.7515	>0.3779	≤0.3565	−0.95138	0.068003	0.05	−1.08467	−0.8181	195.729	<0.0001
>1.0025	>0.0008	>21.7515	>0.3779	>0.3565	−0.92084	0.06132	0.05	−1.04103	−0.80065	225.505	<0.0001

variables are used to establish a tendentious model of investor sentiment, and the logit model is used to estimate the tendency score value (PS value) of investor sentiment in each company. For each company with an indicator of investor sentiment, we select the company that had no investor sentiment in the same year and the closest PS value was used as a matching sample, and examined the difference in the factor variables between the two groups. Table 5 shows the PSM test result and provides further support for hypotheses 1 and 2a.

At the same time, this paper constructs counterfactual research and compares the stock price synchronization (high and low) comparison between investor sentiment and non-investor sentiment under other conditions unchanged. In order to compare the marginal effect of investor sentiment more intuitively, SP, TOPHLD, ETURN, LEV, and SIZE are recoded according to the initial sample mean in the calculation (greater than or equal to the mean part is a group, less than the mean part is a group), and the TOPST and SNCFMI are re-regressed to obtain the tendentious score (probability) and match the tendency score, and the pairing sample according to the nearest neighbor 1-1 match is obtained. Table 6 shows the basic group descriptive statistics before and after PSM pairing, and the selection of the grouping critical value (e.g., 0.0008 in the SP) is mainly taken from the mean level in the original data set at the same time; we re-establish the regression equation, calculate the marginal effects of each key variable (average marginal effect, AME), and compare the marginal effects at different levels, where the SYNCH is analyzed using a paired sample. We compare the variables' (such as SIZE, TOPHLD, and LEV) marginal effects by factor, and the results are shown in Table 7.

It can be noted that when SIZE, TOPHLD, and LEV are taken in larger groups or all taken in smaller groups, and the core variables are taken in larger groups or all taken in smaller groups, insurance company participation in the high group with investor sentiment (TOPST>0.8089 and SNCFMI>1.0025) can reduce share price synchronization by 0.10435 (−1.07784 + 1.04677−1.06674 + 1.04564−0.95442 + 0.92335−0.95061 + 0.9295 = 0.10435) compared with the group of low investor sentiment (TOPST ≤ 0.8089 and SNCFMI ≤ 1.0025); for the high-level investor sentiment group (TOPST>0.8089 and SNCFMI>1.0025), the group with a high proportion of insurance company participation reduced the share price synchronization by 0.16955 (−1.00784−0.95442−1.06674 0.95061 = −0.16955) compared with the group of low proportion of insurance company participation. For the group with low investor sentiment (TOPST ≤ 0.8089 and SNCFMI ≤ 1.0025), the group with a high insurance company participation shareholding is more helpful in reducing the synchronization of share prices by 0.23956 (−1.04677 + 0.92335−1.04564 + 0.9295 = −0.23956) than the group with low-insurance company participation shareholding. It can be seen that for investors with high and low emotional groups, the higher the

proportion of insurance capital shares, the more it helps to reduce stock price synchronicity.

In addition, compared to other institutional investors, the sources of funds, investment strategies, and operating methods of insurance companies show different characteristics. First, longevity and stability are important features of insurance funds. A total of 70% of insurance products have a duration of over 7 years, and life insurance and annuity insurance are mostly long-term insurance products with a duration of more than 10 years to several decades, and the average usable life of insurance funds is over 10 years, so insurance companies' funds are more targeted at long-term investments. Second, the flow of funds for insurance companies is relatively stable. Life insurance payouts are related to the life table of the insured and, apart from force majeure, the life table is relatively stable and insurance companies are able to accurately estimate the outflow of funds. Third, based on the risk constraints on solvency imposed by liability-side repayment pressures and prudential policies, insurers are risk-averse, emphasize capital safety, and place a high emphasis on the level of risk management in the use of capital. Fourth, policies and regulations promote long-term sound investment by insurance companies, continuously expanding the scope and proportion of investment by insurance companies and significantly increasing the cap on the proportion of companies held by insurance companies, while counter-cyclical asset recognition standards and equity method bookkeeping reduce the impact of short-term market fluctuations on the investment returns of insurance institutions and encourage them to strategically increase their holdings in listed companies. In summary, unlike short-sighted institutional investors, insurance institutions prefer to hold listed companies based on a stable, long-term, and concentrated investment strategy, and are more often strategic institutional investors. After holding shares in listed companies, insurance institutions bring their sound business ideas and management experience to listed companies and actively play an external monitoring role. Fifth, insurance institutional investors have a cautious and risk-averse governance style and are involved in supervising the business decisions of enterprises, which is more characteristic of strategic investors. So, the mitigation effect comes from insurance companies.

6 Conclusion

The influence of e-finance on financial markets has attracted more attention from enterprises and academia. As an important factor affecting stock price, investor sentiment has an important influence on the synchronicity of stock price and is prone to produce a "domino effect." Based on the investor sentiment from the perspective of public opinion in the stock market, this paper systematically studies the effect of insurance company participation on the synchronicity of stock prices. The results show that the investor sentiment of the stock market forum will increase the synchronicity of stock prices in the short term and both are positively correlated, while insurance company participation effectively reduces the impact of investor sentiment to share price synchronicity, which played a certain intermediary effect, and the higher the proportion of insurance company shareholdings, the more evident the effect. Because when insurance companies participate in the stock market, they will play a good role in the capital market through corporate governance, and there is a great effect on network forum information to help stabilize investor sentiment, thus reducing the herd effect and the same rise and fall effect of stock price. Through the construction of counterfactual research, we found that insurance company participation in the group of high investor sentiment can reduce the synchronicity of stock price by 0.10435 than the group of low investor sentiment group; for the investor sentiment group, the group with high proportion of insurance companies' shareholdings is more help to reduce the synchronicity of stock prices. The conclusion of this paper has profound implications for investors' investment strategy and the supervision of the capital market by the state.

The conclusion shows that 1) it is important to educate investors and pay more attention to the changes in investor sentiment at the same time in order to prevent their excessive investment behavior affecting market stability; 2) an insurance company is an important institutional investor which plays an important role in the capital market's sustainable development, and the national policy should correctly guide insurance company to participate in the market and avoid disadvantages and create profits for the market, and different types of insurance companies should also make decisions based on their own characteristics; 3) in the case of the rise and fall effect, the government should formulate corresponding policies and regulations to manage institutional investors to prevent risk and the regulatory authorities should strengthen supervision and prevent speculative capital investment behavior; and 4) in the high-speed information-developed society, the relevant information departments of the state should clean up the security market-related information channels and prevent illegal elements from deliberately disturbing the audio-visual behavior, so as to establish the correct investment sentiment orientation and improve the efficiency of capital market pricing.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

FH: conceptualization, methodology, and writing—original draft and editing. BL: formal analysis, investigation, and validation. JY: conceptualization and writing—-review and editing. All authors contributed to the manuscript and approved the submitted version.

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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.

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Appendix A: Variable definitions.

Variable name	Variable description
$SYNCH_{t+1}$	Stock price synchronicity index, a specific calculation process already explained in the previous text
IP_t	Whether the insurance company has a stake, if it does, it is 1; otherwise, it is 0
SP_t	Percentage of insurance companies participating in shares
SN_t	Nature of the insurance company's participation in the stock, if the participating enterprise is state-owned, it is 1, otherwise, it is 0
$TOPST_t$	Natural log of the total number of posts, representing investor concerns
$SNCFMI_t$	Emotional consistency index, the specific calculation process can be explained in the text
RET_t	Average weekly earnings of stocks in the year
$SRET_t$	Standard deviation of the stock's average weekly earnings in the year
$ETURN_t$	Annual excess turnover rate of individual stocks = (current turnover rate - last year's turnover rate)/last year's turnover rate *100%
$TOPHLD_t$	Shareholding ratio of the largest shareholder
P/B_t	Company's market-to-book ratio in the current year
LEV_t	Asset–liability ratio = Total liabilities at the end of the period/Total assets at the end of the period
$SIZE_t$	Size of the assets, the natural equivalent of the total assets at the end of the period
YEAR	Annual dummy variables
INDU	Industry dummy variables

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Study on the coupling coordination and pattern evolution of green investment and ecological development: Based on spatial econometric model and China's provincial panel data

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The study determines the coupling degree of green investment and green ecology in China using kernel density estimation, spatial autocorrelation analysis, and standard deviation ellipse model to empirically evaluate the data of 30 Chinese provinces from 2005 to 2019. Moreover, the study investigates the temporal evolution trend, spatial clustering characteristics, and spatial evolution trend of coupling degree. Although the coupling coordination value of green investment and green ecology gradually increased, it is generally at a low coordination stage. At the same time, regional disparities narrowed with the most significant variability in the eastern region. Moreover, results found that the aggregation effect of the coupling and coordination of green investment and green ecology is more significant, and the high-value aggregation area extended from the lower reaches of the Yangtze River to the midstream region, while the western region is dominated by low-value aggregation. Similarly, the degree of synergy between green investment and green ecology is increased; however, the fragmentation trend is inevitable. At the same time, the center of gravity of coupling coordination shifted to the western regions, and the spatial pattern gradually weakened in the "northeast-southwest" direction. The findings of the study stress that local governments of China should improve the green investment system for green ecological development in the surrounding areas of the Yangtze River Economic Belt. Moreover, it is required to focus on the Northeast revitalization and Western development strategies to promote the synergistic development of green investment and green ecology.

KEYWORDS

green investment, green ecology, coupling coordination, spatial autocorrelation, China

1 Introduction

1.1 Background

In parallel with global economic growth, environmental issues have increased (Khan et al., 2020). About 8.3 million people die each year due to environmental pollution (Khan & Ozturk, 2020) and most cases were found in China as it has ranked second in the world (Landrigan et al., 2018; Gu et al., 2019; Gu et al., 2020). Therefore, it is indispensable to advocate green ecological development in China, as an important for social welfare and human health (Wang et al., 2020). Green investment has involved in the field of renewable energy (Yao et al., 2016; Elahi et al., 2019; Elahi et al., 2022; Elahi et al., 2022) and promotes green economy (Ekeh et al., 2007), which also caters to the strong public demand (Liao and Shi, 2018). May studies have found a positive nexus between green investment and green ecology. Shen et al. (2021) studied the role of natural resource rents, green investment, financial development, and energy consumption in carbon emission reduction using panel data of Chinese provinces in recent years, and concluded that green investment is negatively related to carbon emissions, suggesting that green investment should be promoted to control carbon emissions. Zhu et al. (2014) suggested that environmental regulations as well as green investment can motivate pollution-intensive enterprises in China to maintain green ecology through technological innovation, industrial structure upgrading, and plant relocation. However, some scholars argue that there is a non-linear correlation between the two, that the effect of carbon neutrality and green transformation has a lag, that short-term green investment initiatives will increase the proportion of national eco-industrial R&D investment and weaken green ecological protection, and that the impact of green investment efforts on China's green ecological quality shows a "U" shaped change (Fuyong and Xiang, 2022). There are different views on the study of the coupling mechanism between green investment and green ecology. Many gaps in the quantitative studies on coupling coordination, such as coupling trends and the evolution of the dynamics, have been found. To the best of our knowledge, this is the first attempt to explore the evolutionary trend of green investment and green ecology coupling from temporal and spatial dimensions. Moreover, it provides ideas for green investment and green ecology synergistic development policies in China.

1.2 Literature review and contribution of the study

1.2.1 Green investment promotes green ecology

Some scholars interpret green investment as "socially responsible investment", i.e., investment based on a combination of environmental, social, and economic criteria, which is part of "green finance." Others also innovatively interpreted green investment as the "environmental protection investment." Zhang et al. (2022) used the entropy method and undesirable-SE-SBM model to measure provincial green finance and green development efficiency respectively from 2008 to 2018, and the results showed that green finance can significantly promote green development and improve green ecology after a certain percentage of R&D investment. Mesjasz-Lech (2017) analyzed the relationship between environmental protection expenditures and environmental governance effectiveness for sustainable development using principal component analysis for EU industrial sector related firms and observed that the increase in environmental protection expenditures in most countries was accompanied by improved environmental governance effectiveness. Green investment plays its capital allocation role to provide financial support to green industries for technological innovation, which leads to energy consumption reduction and pollution reduction, and improvement of green ecosystem.

1.2.2 Impact of green ecology on the efficiency of green investment

Green ecology is an important development approach for social progress and green investment efficiency. Most of the existing literature focused on the impact of green ecology on economic growth (Peng et al., 2021; Peng et al., 2021; Zhao et al. 2020; Aldieri et al., 2020) reported that environmental regulations impacted the distribution of financial resources. Vogel (2000) justified that economic integration and green ecological regulation are compatible and that economic integration can provide a certain degree of an effective mechanism for raising regulatory standards. From the perspective of enterprises, Leiter et al. (2011), Testa et al. (2011), and Zhu et al. (2014) argued that a series of government management tools such as environmental controls, financial subsidies, and collection of emission fees can significantly optimize the production methods of enterprises and strengthen their level of green investment. Improving the level of green ecology can effectively enhance corporate investment in energy conservation and emission reduction, thus enhancing environmental protection investment, while green ecology can also enhance corporate environmental protection revenue by increasing corporate investment in energy conservation and emission reduction (Chesney et al. 2011; Jaraite et al. 2014).

1.2.3 Coordination between green investment and green ecology

Despite the green investment is a subdivision of the economy in the field of capital financing, a few studies focused on the coordination relationship between green investment and green ecology. Most of the existing literature focuses on the harmonious relationship between economic growth and green ecology. Kline (2000) believed that high-level economic growth

and a high-quality environment can coexist in ecological cities. Feiock and Stream (2001) found that economic growth and the environment should be integrated and that they should have a harmonious development relationship to promote each other. Gan and Bu (2020) revealed that the coupling coordination between green finance and the eco-environment is developing from an uncoordinated level to a well-coordinated level, but failed to analyze their coupled coordination relationship in depth. On the one hand, Liu et al. (2018) argued that the social welfare brought by economic development can significantly improve the quality of the environment and gradually lead to the benign development of the overall environment. On the other hand, the gradual improvement of the environment can optimize the economic structure, stimulate economic vitality and adjust the economic scale.

By comparison of the above studies, it is found that most of the existing studies on green investment and green ecology focus on the improvement effect of green investment on green ecology and the promotion effect of green ecology on green investment efficiency, and there are still research gaps on issues of the coupling and coordination of green investment and green ecology, which need to be further explored. The existing studies on the spatial distribution of coupling and coordination mostly focused on the field of spatial clustering, and lack of in-depth exploration of the evolution of spatial and temporal patterns. Therefore, the current study selects general indicators of green investment and green ecology in 30 Chinese provinces and explores the coupling characteristics of green investment and green ecology in China from 2005 to 2019. While studying the temporal evolution trend of coupling coordination, it also delves into the spatial evolution characteristics of coupling coordination and examines whether there is a coupling effect between green investment and green ecology. Furthermore, the study provides ideas for synergistic development of green investment and green ecology in China.

2 Materials and methods

2.1 Research methods

Common methods of variable modeling studies include panel data (Khelfaoui et al., 2022; Khelfaoui et al., 2022), bias correction (Ahmed et al, 2021), structural equation modeling (Ahmed et al., 2021), and sample analysis (Ahmed et al., 2019), among others. The coordination model is used to estimate the degree of interaction between green investment and green ecology. Using the kernel density function, another estimation method is constructed to study the time-series evolution of the interaction between green investment and green ecological development. In addition, we used the spatial autocorrelation analysis method (*Moran's I index, Getis-Ord Gi* index*) for exploratory spatial data analysis (ESDA) and the spatial standard deviational ellipse model to analyze the spatial global characteristics and local spatial clustering differences in the coordination of green investment and green ecology coupling.

2.1.1 Pre-processing of data

As the indicators of green investment and green ecology differ in terms of units and areas of expertise. Therefore, to eliminate the influence of the innate defects of the system indicators on the empirical results, the values of the indicators should be carried out using dimensionless processing. Based on this theory, the indicators were standardized into positive and negative indicators using maximum difference denormalization (Wang et al., 2019).

$$Z_{ij} = \frac{X_{ij} - Min(X_j)}{Max(X_j) - Min(X_j)} \left(\text{When } X_{\text{ij}} \text{ is a positive indicator}\right) \tag{1}$$

$$Z_{ij} = \frac{Max(X_j) - X_{ij}}{Max(X_j) - Min(X_j)} \left(\text{When } X_{\text{ij}} \text{ is a negative indicator}\right) \tag{2}$$

where X_{ij} denotes the value of indicator i in the j-th year. $Min(X_j)$ and $Max(X_j)$ represent the minimum and maximum values of the indicator among all indicators in the j-th year, respectively. Z_{ij} is the final standard value. To eliminate the interference of human factors on the index values, the standardized index Z_{ij} is processed by the entropy method to obtain the weights W_{ij} (Cao et al., 2020). The results of the weights are given in Table 1.

2.1.2 Coupling coordination model

The concept of coupling is taken from physics and it refers to the process in which two or more systems interact and thus influence each other. Many scholars used this concept in the fields of economics, ecology, and sociology. Similarly, in this study, we considered the "green investment-green ecology" system as the research object. Following Tang (2015), a coupling coordination model consisting of a coupling degree model and a coordination degree model was constructed.

$$U_f = \sum_{j=1}^{m} X_{ij} \cdot W_{ij} \quad U_e = \sum_{j=1}^{n} Y_{ij} \cdot W_{ij} \tag{3}$$

$$C = \sqrt{U_f \cdot U_e / \left(U_f + U_e\right)^2} \quad T = \partial \cdot U_f + \beta \cdot U_e \tag{4}$$

$$D = \sqrt{C \cdot T} \tag{5}$$

where C is the coupling degree, T is the integrated coordination index of green investment and green ecosystem. ∂ and β are the undetermined coefficients of green investment and green ecosystem, respectively, which are listed at the same level in this paper. Therefore, both are brought in with a value of .5 (Ai

TABLE 1 Construction of a systematic index of green ecology and green investment.

	System layer	Element layer	Indicator layer (indicator code)	Unit	Indicator attribute	Weight
Green ecology	Green growth	Economic growth	GDP *per capita* (X1)	Yuan	+	0.0367
			Local fiscal revenue *per capita* (X2)	Yuan	+	0.0336
		Ecological economy	Energy consumption per ten thousand yuan of GDP (X3)	Tons of standard coal/million yuan	–	0.0401
			Industrial SO2 emissions per ten thousand yuan of GDP (X4)	kg/million yuan	–	0.0403
			Industrial wastewater discharge per ten thousand yuan of GDP (X5)	kg/million yuan	–	0.0402
		Output level	Labor productivity in primary industry (X6)	Yuan/person	+	0.0377
			Labor productivity in secondary industry (X7)	Yuan/person	+	0.0373
			Labor productivity of tertiary industry (X8)	Yuan/person	+	0.0358
			Value-added ratio of tertiary industry (X9)	%	+	0.0378
		Standard of living	Per capita disposable income of urban residents (X10)	Yuan	+	0.0364
			Net income of rural residents (X11)	Yuan	+	0.0365
			Per capita housing area (X12)	m^2	+	0.0376
	Green welfare	Public service	Per capita park green space (X13)	m^2/person	+	0.0388
			Green coverage rate of built-up areas (X14)	%	+	0.0400
			Decontamination rate of urban refuse (X15)	%	+	0.0381
			Comprehensive utilization rate of industrial solid waste (X16)	%	+	0.0396
		Resource consumption	Per capita domestic water consumption (X17)	L/person	–	0.0404
			Per capita energy consumption (X18)	kg standard coal/person	–	0.0404
	Resources and environment	Environmental pressure	Industrial SO2 emission per unit land area (X19)	t/km^2	–	0.0404
			Industrial wastewater emission per unit land area (X20)	t/km^2	–	0.0401
		Ecological quality	Forest coverage rate (X21)	%	+	0.0371
			The ratio of the area of nature reserves to the area under the jurisdiction (X22)	%	+	0.0362

(Continued on following page)

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TABLE 1 (*Continued*) Construction of a systematic index of green ecology and green investment.

	System layer	Element layer	Indicator layer (indicator code)	Unit	Indicator attribute	Weight
Green investment	Environmental pollution control investment	Investment in industrial pollution control (Y1)		Million yuan	+	0.0351
		Investment in urban environmental infrastructure construction (Y2)		Million yuan	+	0.0337
		"Three simultaneous" project investment in environmental protection engineering (Y3)		Million yuan	+	0.0258
	Water conservancy construction investment	Water construction investment (Y4)		Million yuan	+	0.0303
	Forestry investment	Forestry investment (Y5)		Million yuan	+	0.0338

et al., 2016). D is the integrated coordination degree of green investment and green ecosystem.

2.1.3 Kernel density estimation

Taking the coupling coordination value as the research object, the kernel density estimation method is applied to explore the time evolution pattern of the coupling relationship between green investment and green ecology. The kernel density estimation is based on non-parametric tests, which evaluate and analyzes the probability densities of variables, and ultimately investigate the evaluation method of data distribution dynamics. While in the fields of management, geography, and economics, the probability density distribution characteristics of the specified years within the study period of the sample can be used to compare the temporal evolution pattern of the study object using a given function.

$$f_n(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(X - X_i) = \frac{1}{nh}\sum_{i=1}^{n} K_h\left(\frac{X - X_i}{h}\right) \tag{6}$$

where $K\left(\frac{X-X_i}{\mathrm{h}}\right)$ is the kernel function with bandwidth. In this study, the default bandwidth of Stata software is used, while the Gaussian kernel function is used. For the implementation of kernel density, we have followed Jiang et al. (2019).

$$\text{Gausian} = \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-1/2t^2} \tag{7}$$

2.1.4 Convergence function

To explore the variability characteristics of a certain research object in the research region, the convergence function (σ) can measure the variability of a certain index. In this study, the coupling coordination value is brought into the convergence function for a preliminary study on the variability of the coupling coordination between green investment and green ecology in each region of China. Following the studies of Wu et al. (2020), the specific equation can be written as:

$$\sigma_t = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\log(Y_{it}) - \frac{1}{n}\log(Y_{it})\right]^2} \tag{8}$$

where Y_{it} shows the coupling coordination value of province i in year t and σ_t represents the log standard deviation of n provinces in year t.

2.1.5 Spatial clustering analysis

The spatial autocorrelation method is a type of exploratory spatial data analysis to explore the interconnections and dependencies of variables among regions within the research object that consisted of two theoretical models i.e., global spatial autocorrelation and local spatial autocorrelation (Li et al., 2020). In this paper, we used *Moran's I* index and *Getis-Ord Gi** index, which are commonly used in the application of indices to focus

on the spatial local clustering characteristics among provinces, autonomous regions, and municipalities that are directly under the central government.

Global spatial autocorrelation (*Global Moran's I*):

$$I_g = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\left(X_i-\bar{X}\right)\left(X_j-\bar{X}\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\right)\sum_{i=1}^{n}\left(X_i-\bar{X}\right)^2} \tag{9}$$

Local spatial autocorrelation (*Local Moran's I*):

$$I_l = \frac{n\left(X_i-\bar{X}\right)}{\sum_{i=1}^{n}\left(X_i-\bar{X}\right)^2}\sum_{i\neq j}^{n}W_{ij}\left(X_j-\bar{X}\right) \tag{10}$$

*Getis-Ord Gi** index:

$$G_i^*(d) = \sum W_{ij}(d)X_i \Big/ \sum X_{ij} \tag{11}$$

where I_g is the global Moran index, I_l is the local Moran index, n is the sample size, X_i and X_j denote the coupling coordination values of the i and j provinces and municipalities respectively. W_{ij} is the spatial weight that indicates the spatial relationship between regions within the research object. In this paper, we used the adjacent spatial weight as the operational value, i.e., adjacent is recorded as 1 and non-adjacent is recorded as 0.

$$Z = \frac{I-E(I)}{\sqrt{VAR(I)}} \tag{12}$$

If $Z>0$ and passes the Z-value significance test, it indicates that the coupling coordination value is significant and positively correlated, while if $Z<0$ and passes the Z-value significance test, it indicates that the coupling coordination value is significant and negatively correlated; otherwise, the correlation is not significant.

2.1.6 Spatial standard deviational ellipse

This paper carries out an empirical study using a spatial standard deviational ellipse to investigate the spatial global characteristics for the coupling and coordination characteristics of green investment and green ecology. The standard deviational ellipse focuses on revealing the global characteristics of geographical elements' spatial distribution and belongs to the statistical analysis method of spatial pattern. The model mainly describes the spatial distribution dynamics of geographical elements quantitatively with parameters such as the center of gravity, rotation angle θ, x-axis standard deviation, and y-axis standard deviation (Gong, 2002).

$$X = \frac{\sum_{i=1}^{n}W_iX_i}{\sum_{i=1}^{n}W_i};\ Y = \frac{\sum_{i=1}^{n}W_iY_i}{\sum_{i=1}^{n}W_i} \tag{13}$$

TABLE 2 Classification of coupling coordination level.

Range of D value	Types of classification
0.81 < D ≤ 1.00	Complete coordination stage (V)
0.61 < D ≤ 0.80	Good coordination stage (IV)
0.41 < D ≤ 0.60	Basic coordination stage (III)
0.21 < D ≤ 0.40	Low coordination stage (II)
0.00 < D ≤ 0.20	No coordination stage (I)

$$\sigma_x = \sqrt{\frac{\left(\sum_{i=1}^{n}W_iX_i^*\cos\theta - W_iY_i^*\sin\theta\right)^2}{\sum_{i=1}^{n}W_i^2}};\quad \sigma_y = \sqrt{\frac{\left(\sum_{i=1}^{n}W_iX_i^*\sin\theta - W_iY_i^*\cos\theta\right)^2}{\sum_{i=1}^{n}W_i^2}} \tag{14}$$

$$tan\,\theta = \frac{\left(\sum_{i=1}^{n}W_i^2X_i^{*2} - \sum_{i=1}^{n}W_i^2Y_i^{*2}\right) + \sqrt{\left(\sum_{i=1}^{n}W_i^2X_i^{*2} - \sum_{i=1}^{n}W_i^2Y_i^{*2}\right)^2 - 4\sum_{i=1}^{n}W_i^2X_i^{*2}Y_i^{*2}}}{2\sum_{i=1}^{n}W_i^2X_i^*Y_i^*} \tag{15}$$

where (X,Y) is the barycentric coordinate of the coupling coordination value of the green investment and green ecology. (X_i, Y_i) is the spatial coordinate of the study area, and (X_i^*, Y_i^*) is the relative coordinate of each point in the study area from the regional coupling coordination center. W_i is the value of coupling coordination between green investment and green ecology in each region. σ_x and σ_y are the standard deviation along the X-axis and Y-axis, respectively. Similarly, θ shows the deflection angle.

2.2 Sources of indicator and classification

2.2.1 Construction of indicator system and sources

Green investment indicators and green ecological indicators are complex systems, including social, economic, environmental, and other factors (Peng et al, 2018; Peng et al, 2020; Zhao et al, 2021; Zhong et al, 2021). This paper upholds the principles of indicator availability, comprehensiveness, and scientific nature. Moreover, following Fei et al. (2020), He et al. (2017), and Lu et al. (2017) we selected a total of three first-level indicators for green ecosystems such as green growth, green welfare, and resource environment. Similarly, a total of three first-level indicators are selected from green investment such as investment in environmental pollution control, investment in water conservancy construction, and investment in forestry. The detail of the selection of indicators is given in Table 1.

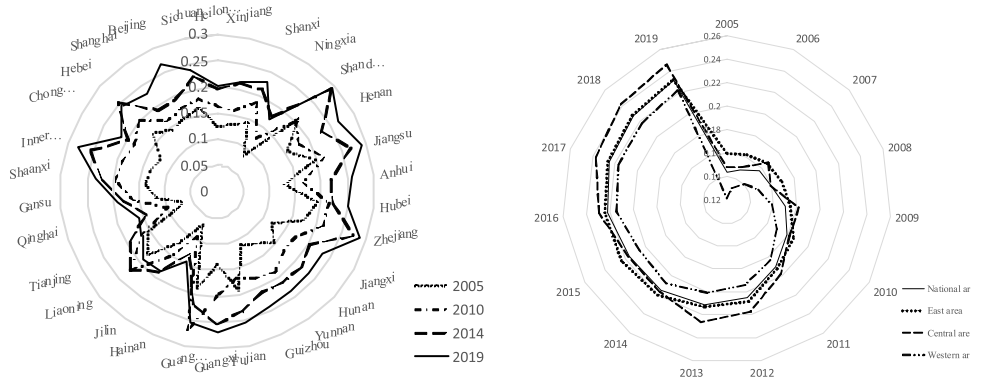

FIGURE 1
Evolution values of coupling coordination.

TABLE 3 Evolution of types of coupling coordination.

Provinces	2005	2010	2014	2019	Provinces	2005	2010	2014	2019
Heilongjiang1	I	I	I	II	Guangxi	I	I	II	II
Xinjiang	I	I	II	II	Guangdong	I	II	II	II
Shanxi	I	I	II	II	Hainan	I	I	I	I
Ningxia	I	I	I	I	Jilin	I	I	I	I
Shandong	II	II	II	II	Liaoning	I	II	II	I
Henan	I	I	II	II	Tianjin	I	I	I	I
Jiangsu	I	II	II	II	Qinghai	I	I	I	I
Anhui	I	I	II	II	Gansu	I	I	I	I
Hubei	I	II	II	II	Shaanxi	I	I	II	II
Zhejiang	I	II	II	II	Inner Mongolia	I	I	II	II
Jiangxi	I	I	II	II	Chongqing	I	I	I	II
Hunan	I	I	II	II	Hebei	I	II	II	II
Yunnan	I	I	II	II	Shanghai	I	I	I	II
Guizhou	I	I	II	II	Beijing	I	I	I	II
Fujian	I	I	II	II	Sichuan	I	I	II	II

Shows no coordination stage (I). Shows low coordination stage (II).

The data were obtained from the China Statistical Yearbook on Environment, the China Water Statistical Yearbook, the China Forestry Yearbook, and the statistical yearbooks of each province from 2005 to 2019. The vector map of China was used to visualize the conclusions which it is derived by scanning the administrative boundaries of the region, and the individual missing values are filled in by linear regression interpolation.

2.2.2 Coupling feature classification

Coordination degree refers to studying the degree of coupling while considering the coordination degree between systems, which is used to explore the good or bad coupling degree between green investment and green ecosystem, usually, the value of D is in the range of 0 and 1. This paper draws on the research results of Gan and Bu (2020) to make the following classification of coordination degree level (Table 2).

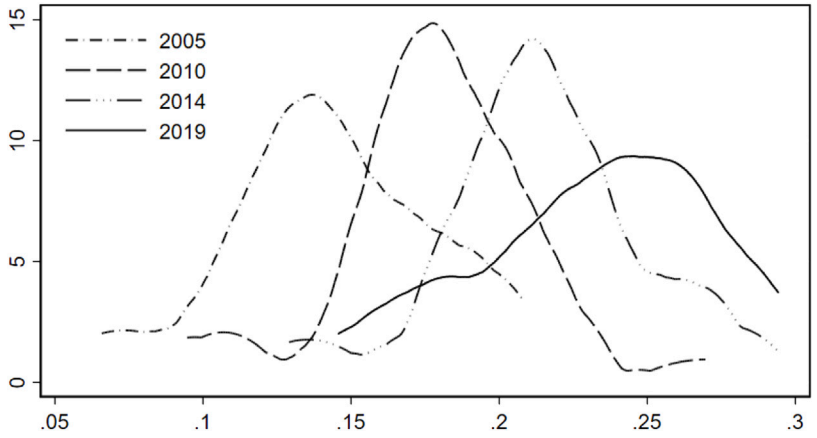

FIGURE 2
Kernel density distribution of coupling coordination.

3 Results

3.1 Analysis of coupling coordination

The coupling coordination values of green investment and green ecology were estimated based on the coupling coordination model. In particular, we selected 2005, 2010, 2014, and 2019 as time points to study the temporal characteristics of the coupling coordination in various provinces of China (Figure 1). Furthermore, the provinces were divided into eastern, central, and western regions to determine the spatial distribution of the coupling coordination between green investment and green ecology.

The results depict that from 2005 to 2019, the coupling coordination values of provinces showed a continuously increasing trend, but all of them were at the stage of serious disorder, and the coupling coordination values also vary widely between regions. It shows that the combination of green investment and green ecology in China has become deeper during the study period, but the interaction between the two is relatively chaotic and the development trends are different between regions. For instance, from 2005 to 2010, the coupling coordination values were generally larger in the eastern provinces of China particularly, Guangdong, Liaoning, and Shandong. It indicates that the superior economic advantages and infrastructure in the eastern regions provide a solid foundation for the combination of green investment and green ecology. Similarly, from 2010 to 2019, the coupling coordination values of developed eastern coastal provinces such as Jiangsu, Shanghai, Zhejiang, and Guangdong still ranked in the first echelon, but the mean value of coupling coordination values in the central region is higher than that in the eastern region during the period. It means that the coupling coordination values of eastern provinces particularly, Liaoning and Tianjin are too low and there is a certain degree of polarization.

Regarding types of coordination (Table 3), the types for coordinating green investment and green ecology in 2005–2019 are only the no coordination type and the low coordination type. Specifically, the type of coordination between green investment and green ecology in China from 2005 to 2010 is dominated by the type of no coordination, and the coordination relationship between green investment and green ecology is generally in a chaotic state during the period. From 2014 to 2019, the number of provinces in the low coordination type gradually increased by 66.7% and 76.7% of the total in 2014 and 2019, respectively. This implies that during this period China's green investment and green ecology started the coordination phenomenon; however, the overall coordination level is still not high.

3.2 Time evolution

We used the kernel density estimation method and determined the evolution characteristics of the coupling coordination between green investment and green ecology. Figure 2 illustrates that from 2005 to 2019, there is an overall shift to the right in the center of the kernel density curve of the coupling coordination between green investment and green ecology, and the magnitude of the shift gradually increases. However, the change interval has decreased year by year. It suggests that the coupling coordination value of Chinese provinces has increased continuously over 15 years and the regional gap has narrowed.

From 2005 to 2019, the kernel density curve shows a shift from multiple peaks to a single peak. In 2005, there are two peaks, of which the kernel density value corresponding to the first peak is smaller than the second one, indicating a clear

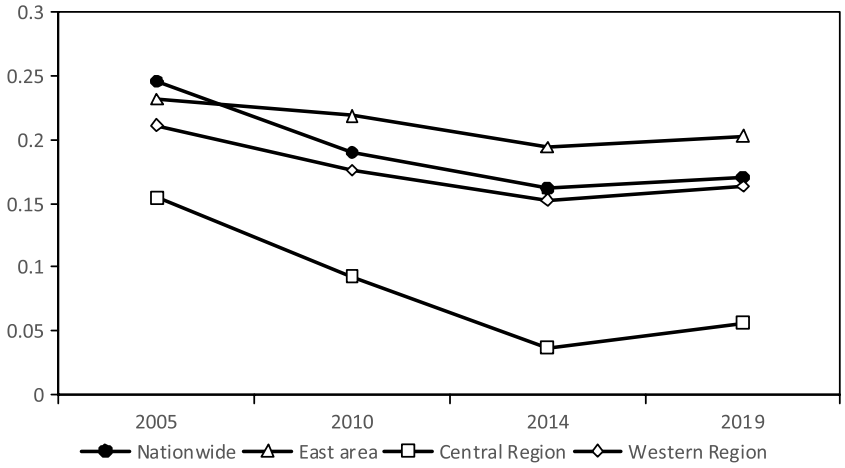

FIGURE 3
Convergence analysis of the coupling coordination.

TABLE 4 Global *Moran'I* indexes.

Year	*Moran'I*	*E(I)*	*Z(I)*	*P*
2005	0.1228	−0.0345	2.0591	0.0395
2010	−0.0153	−0.0345	0.2571	0.7971
2014	0.0104	−0.0345	0.5941	0.5524
2019	0.0901	−0.0345	1.6215	0.1049

polarization of the coupling coordination between green investment and green ecology in each province. In 2010, the kernel density curve consists of the main peak and two side peaks, suggesting that the polarization characteristics of the coupling coordination of green investment and green ecology have been expanded gradually. The shape of the kernel density curve in 2014 is similar to that in 2005; however, the number of peaks decreased as compared to 2010 until the kernel density curve developed into a single peak in 2019. It means that the regional differences in the coupling coordination of green investment and green ecology in each province decreased gradually. This indicates that a higher level of agglomeration phenomenon and polarization characteristics disappeared.

From 2005 to 2019, the kurtosis of the kernel density curve of green investment and green ecological coupling coordination shifts to the right. It shows a shift from a "sharp peak" to a "broad peak." From 2005 to 2014, the left peak of the kernel density curve gradually increased, and the spike feature of the crest become more and more significant, which means that the coupling coordination value of the green investment and green ecology increased in each province of China. Furthermore, Figure 2 illustrates that the kurtosis of the kernel density curve decreased year by year from 2014 to 2019, while the crest pattern gradually flattened out and evolved toward a broad peak feature. This implies that the number of regions with the coupling coordination value of the green investment and green ecology corresponding to each crest was expanded.

3.3 Convergence analysis

The convergence function (σ) was used to estimate the differences in the coupling coordination of green investment-green ecology among various regions of China (Figure 3). At the national level, from 2005 to 2014, the σ values continue to decline, indicating a gradual decrease in the variability of the coupling coordination between green investment and green ecology in China. Figure 3 illustrates that the value of σ increased slightly from 2014 to 2019, but it is still smaller than the σ values in 2005. It reveals an overall decrease in the variability of coupling coordination over the study period. At the regional level particularly in eastern and western regions, the values of σ experienced an evolutionary trend of slowly decreasing and then slowly increasing. The overall coupling coordination showed a convergence trend. From 2005 to 2014, the values of σ in the central region declined rapidly and then increased slowly from 2014 to 2019, which indicates a significant overall decrease in the variability of coupling coordination in the region. The order of σ values in the three regions is the highest in the eastern region, the second-highest in the western region, and the smallest in the central region, which shows that the central region has the least variability in the

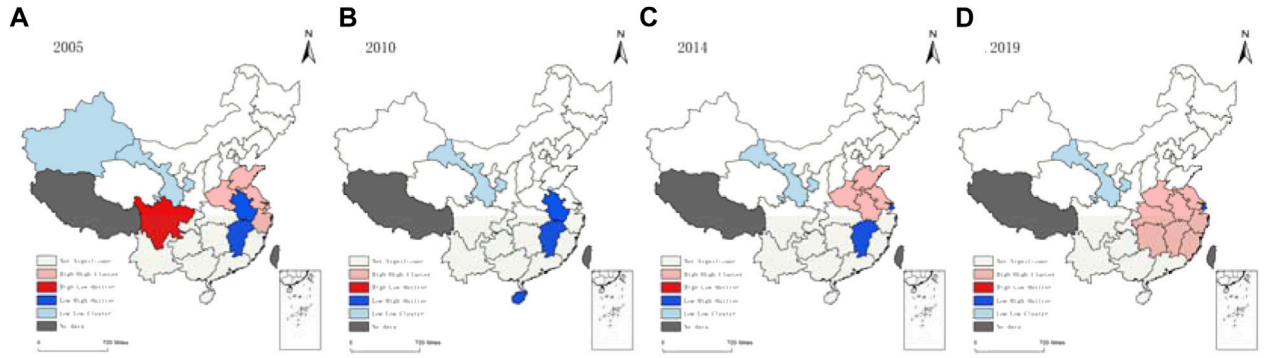

FIGURE 4
Local indicators of spatial association of the coupling coordination. **(A)** 2005, **(B)** 2010, **(C)** 2014, **(D)** 2019.

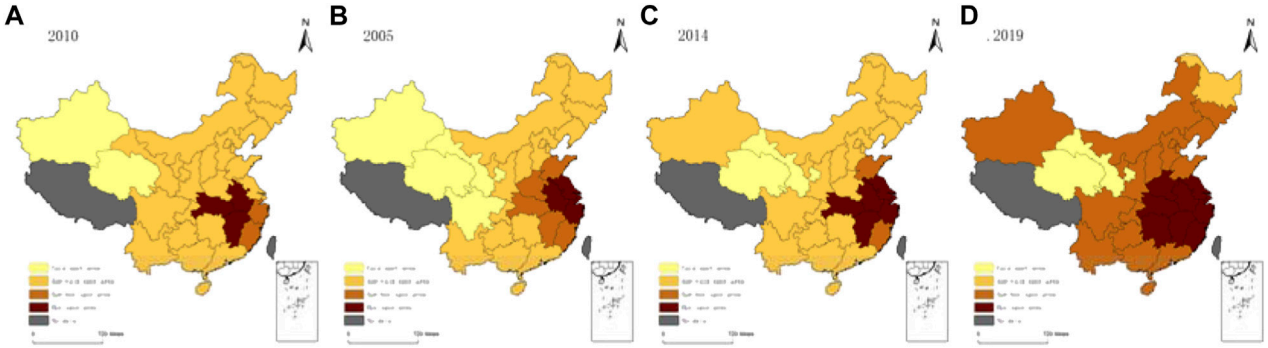

FIGURE 5
Cold and hot spot areas of the coupling coordination degree. **(A)** 2010, **(B)** 2005, **(C)** 2014, **(D)** 2019.

coupling coordination characteristics of green investment and green ecology.

3.4 Spatial clustering analysis

The coupling coordination value of the green investment and green ecology were taken as the research variable and calculated Moran's I index for 2005, 2010, 2014, and 2019. We performed 9999 randomizations to test the significance level (Table 4). In 2005, 2014, and 2019, the *Moran'I* index was greater than zero, and it showed an evolutionary trend of first decreasing and then increasing. It demonstrates that the coupling coordination of green investment and green ecology has spatial clustering characteristics at this time, and the clustering characteristics were continuously strengthened in 2014 and 2019. In 2010, the *Moran'I* index is less than zero, which means that the coupling coordination at this time does not have the characteristics of spatial agglomeration, but presents a certain degree of dispersion. Except in 2005, when the *Z*-value of coupling coordination passes the 5% significance test, the rest of the time points are not significant at the 5% or 10% statistical level. However, it is not proved that there is a lack of autocorrelation of coupling coordination between green investment and green ecology in China because the selection of spatial weights and the differences between regions may lead to insignificant coupling coordination values. Therefore, the spatial correlation analysis using the local *Moran'I* index is required.

The local Moran index can reasonably analyze the spatial autocorrelation of the study area. The local indicators of spatial association (*LISA*) clustering maps are plotted at a 5% significance level. Figure 4 illustrates that the coupling coordination of green investment and green ecology in China from 2005 to 2019 possesses four types of spatial agglomeration: 1) Significantly high-high type, i.e., the coupling coordination values of both itself and the surrounding areas are high, and the differences between regions

TABLE 5 Shift of the center of gravity for coupling coordination values and standard deviation ellipse parameters.

Year	Barycentric coordinates		Center of gravity			Standard deviation (km)		Angle of rotation	Oblateness
	Longitude (°E)	Latitude (°N)	Direction	Distance (*km*)	Velocity (*km/a*)	Minor axis	Major axis		
2005	112.59	33.49	—	—	—	964.93	1,098.26	28.99	1.138
2010	112.34	33.43	Southwest	40.02	8.04	959.13	1,130.56	28.19	1.179
2014	112.29	33.52	Northwest	18.18	4.55	987.36	1,119.94	31.01	1.134
2019	112.27	33.38	Southwest	26.10	5.22	981.72	1,108.10	28.35	1.129

are small. It reveals the phenomenon of high-value aggregation. In terms of its spatial distribution, it was mainly concentrated in Shandong, Jiangsu, Shanghai, Zhejiang, and Henan in 2005, while the number of high-value aggregation areas gradually disappeared in 2010. The number of significantly high-high type areas continued to increase from 2010 to 2019, extending to the middle and lower reaches of the Yangtze River provinces and their surrounding areas. 2) Significantly high-low type, i.e., the self-coupling coordination value is high, but the surrounding areas are small, and the spatial differences are more obvious. The regional distribution of this spatial agglomeration type is limited and existed only in Sichuan Province in 2005. 3) Significantly low-high type, i.e., the self-coupling coordination value is low, but the coupling coordination values of surrounding areas are high and the spatial differences are more significant. From 2005 to 2014, the spatial distribution is more regionally concentrated, mostly located in Anhui and Jiangxi provinces, and occasionally in Hainan and Shanghai in individual years. 4) Significantly low-low type i.e., the coupling coordination value between itself and the surrounding areas is low, and the spatial difference is small, showing a low-value aggregation. In 2005, a significantly low-low type is distributed only in Xinjiang and Gansu. After 2005, there are few low-value aggregation regions in Gansu Province.

The *Getis-Ord Gi** index can be calculated for each element of the research data, and the statistical method is different from the local Moran index, which is an important complement to local spatial autocorrelation. Therefore, this paper further explores the clustering characteristics of the coupling coordination of green investment and green ecology in China and divides them into cold spot areas, sub-cold spot areas, sub-hot spot areas, and hot spot areas using the natural break method (Figure 5). The results can be reported as: 1) The number of hot spot areas increased year by year, gradually developing from the coastal provinces in the lower reaches of the Yangtze River to the provinces in the middle and lower reaches of the Yangtze River and its surrounding areas, demonstrating that these provinces have higher coupling coordination values, have advantages in the combination of green investment and green ecology, and presented a high-value aggregation trend. 2) During 2005 and 2014, the number of sub-hot spot areas decreased gradually, initially concentrated in the central provinces of East China and some central provinces, and gradually shrinking to the coastal areas of East China. In 2014 and 2019, the number of sub-hot spot areas grew rapidly to 18 and was distributed in the eastern, central, and western regions. There are large differences in coupling coordination values between regions. 3) The development trend of the number of sub-cold spot areas is opposite to that of sub-hot spot areas, experiencing a development trend of gradual expansion followed by rapid shrinkage, and in 2019 there is Heilongjiang Province belonged to sub-cold spot areas. The regional differences are large. 4) The number of cold spot areas gradually decreased and is concentrated in the western region. After 2014, only Qinghai and Gansu existed. It shows that the low-value aggregation area of the coupling coordination value is gradually

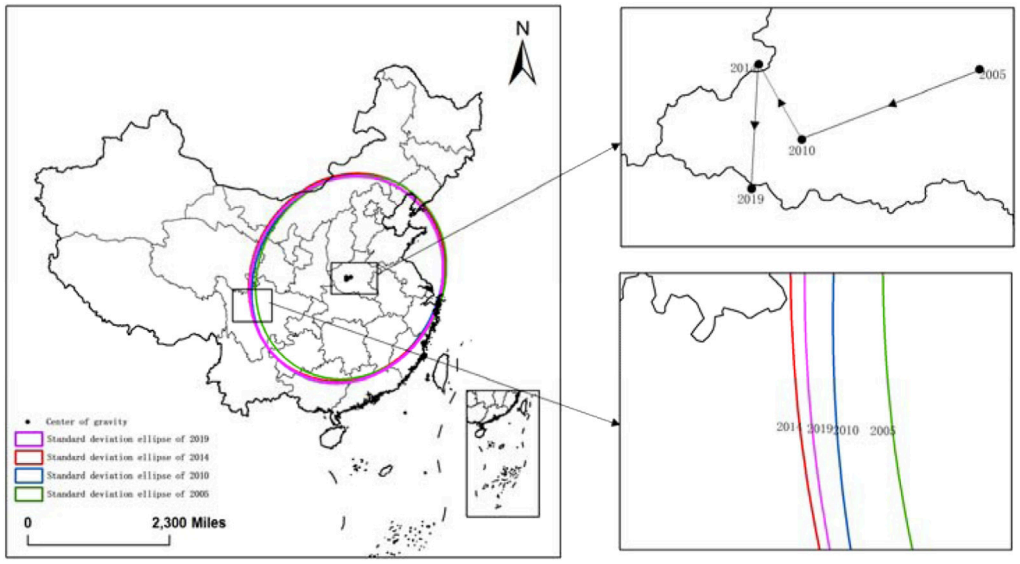

FIGURE 6
Spatial distribution of evolutionary trend of the coupling coordination degree.

shrinking in the western region, and the regional differences are small.

3.5 Analysis of spatial evolution

After proving the existence of spatial clustering characteristics of the coupling coordination of green investment and green ecology in China, this study further applies the center of gravity-standard deviation ellipse method to investigate the spatial evolutionary dynamics of the coupling coordination values. And, 2005, 2010, 2014, and 2019 are selected to study the spatial distribution characteristics of the coupling coordination of green investment and green ecology (Table 5; Figure 6).

Examining the distribution, distance, and rate of movement of the center of gravity in the center of gravity model, the centers of gravity of the coupling coordination between green investment and green ecology in China are all distributed in Henan Province. It indicates that in the generalized east-west direction, the combination of green investment and green ecology in eastern China is generally better than that in the western region. It is found that the center of gravity of the coupling coordination value in 2005 is located in Pingdingshan City, Henan Province. From 2005 to 2010, the center of gravity of the coupling coordination value shifted to the southwest from Baofeng County (Pingdingshan City) to Lushan County (Pingdingshan City), moving 40.02 km and 8.04 km/a, respectively. It is the farthest distance and the fastest moving rate. Similarly, the center of gravity shifted to the northwest from 2010 to 2014, moving from Baofeng County to Song County in Luoyang City, but the distance and rate of movement decreased to 18.18 km and 4.545 km/a, respectively. Moreover, the center of gravity of the coupling coordination value shifted to the southwest again in 2014 and 2019 and approached the edge of Nanyang City, at this time the moving distance increased slightly and the moving rate increased slowly. The above analysis shows that the center of gravity of China's green investment and green ecological coupling coordination generally showed a westward shift in the east-west direction, and shifts northward and then southward in the north-south direction. It is gradually developed towards the middle reaches of the Yangtze River at the geographical level. The moving speed of the center of gravity generally showed a trend of "accelerating to gradually decreasing to slowly increasing."

From the evolution of the rotation angle, the spatial pattern of the coupling coordination between green investment and green ecology in China from 2005 to 2019 showed a "northeast-southwest" phenomenon and a shift toward the "north-south" direction, while the rotation angle θ presents an overall trend of fluctuating declined. This indicated that the "northeast-southwest" spatial distribution pattern has a certain degree of tendency to weaken. Specifically, the rotation angle θ changed by 0.8° from 2005 to 2010, which showed that the spatial pattern of coupling coordination between green investment and green ecology has shifted from "northeast-southwest" to "due north-south" by 0.8°. From 2010 to 2014, the rotation angle θ increased to 31.01°, and the spatial distribution of the coupling coordination type shifted to the "due north-south" direction again by 2.66° from 2014 to 2019.

From the analysis of the length of the main axis, the standard deviation of both the major axis and the minor axis of the standard deviation ellipse from 2005 to 2019 showed a fluctuation with an increasing trend. It indicated that the coupling coordination between

green investment and green ecology in China is gradually dispersed in the "northeast-southwest" and "southeast-northwest" directions. From the change of the major axis, the standard deviation of the major axis in 2005 gradually expanded from 1,098.26 to 1,130.56 km in 2010, suggesting that the coupling coordination is dispersed in the spatial direction of "northeast-southwest". The standard deviation of the major axis decreased from 1,130.56 to 1,108.10 km from 2010 to 2019. It showed that the coupling coordination gradually polarized in the "northeast-southwest" direction during this period. From the change of the minor axis, the standard deviation of the minor axis decreased from 2005 to 2010 and from 2014 to 2019, which means that the coupling coordination is polarized in the "southeastward-northwestward" direction. The standard deviation gradually increased from 2010 to 2014. It indicated that the coupling coordination is dispersed in the direction of "southeastward - northwestward." The change of the flatness rate fluctuates from 1.138 to 1.129 during the study period. This implies that the coupling coordination between green investment and green ecology in China showed a local aggregation trend, and the overall aggregation degree gradually decreased.

4 Discussion

In this study, the coupling coordination characteristics of green investment and green ecology are studied in spatial and temporal dimensions. In particular, the coupling coordination is explored in three aspects: temporal evolution characteristics, spatial clustering analysis, and spatial pattern evolution.

Regarding the temporal evolution of coupling coordination, the national coupling coordination value developed from 0.1432 to 0.2314 from 2005 to 2019, and the coupling coordination value of the green investment and green ecology gradually increased. However, it is still at the stage of serious unbalanced development. Similar to the study of Gan and Bu (2020), who concluded that the coupling coordination of the green financial system and ecology was changed from the uncoordinated stage to the well-coordinated stage. The center of the kernel density curve shifted to the right, but the changed interval decreased year by year. At the same time, the number of peaks gradually decreased, showing a "spike-broad peak" transformation, indicating that the coupling coordination values of Chinese provinces have narrowed during the study period. Therefore, the clustering phenomenon is more significant, and the polarization characteristics have disappeared significantly. The results of the convergence analysis revealed that the differences in coupling coordination decreased across Chinese provinces, but the most significant difference was found in the eastern region. Probably because China first proposed the concept of ecological civilization in 2007, thus the coupling coordination value of green investment and green ecology gradually increased. Until 2016 when China announced the industrial green development and the green financial system planning, the green investment was formally involved in the green ecological construction, while the coupling coordination was still in the primary stage. However, green development policies vary from region to region, and regional characteristics were formed with the evolution over time. Thus the gap in regional coupling coordination was decreased. Among them, the economic base and geopolitical advantages of the eastern region are better than those of the central and western regions. The polarization phenomenon among the provinces in the eastern region is also the most significant, and therefore there is a greater variability of coupling coordination is found.

Regarding the analysis of spatial cluster, whether it is the local *Moran'I* index or the *Getis-Ord Gi** index, the spatial distribution characteristics showed that the high-value agglomeration area developed gradually from the Yangtze River inlet and its vicinity to the middle reaches of the Yangtze River, making it a highland for the synergistic development of green investment and green ecology, and the radiation effect on the neighboring provinces has always existed, which is similar to the conclusion of other studies, for instance, Yao et al. (2014). In these studies, the significant economic and ecological agglomeration characteristics in the eastern part of China were found because China proposed the strategy of Yangtze River Golden Waterway, the Yangtze River estuary area represented by Shanghai, Jiangsu, Anhui, and Zhejiang which has a strong economic advantage. The amount of related environmental pollution control investment, water conservancy construction investment, and forestry investment is also more than sufficient. The geographical situation is mostly plain, coupled with a variety of policy resources, which can ensure that green investment is efficiently and sufficiently invested in the field of green ecology. In China, the combination of green ecology and green ecology is in the first echelon. However, low-value aggregation regions are only distributed in and around Gansu with the least obvious coupling coordination characteristics. Perhaps because the economic base of the western region represented by Gansu is relatively weak, and the ecological environment is relatively poor, the combination of the two has a long way to go.

Regarding spatial pattern evolution, the center of gravity of the coupling coordination of green investment and green ecology generally shifted 53.84 km to the southwest. The results are in line with the studies of Lai et al. (2020), who found the coupling coordination of ecology and economy in the central and western provinces gradually increased. Probably because the implementation of the Belt and Road and the Western Development Strategy proposed by China, led to the strengthening of the state's support for the western and southwestern regions, providing an important policy backing for the economic development of the central and western regions and laying the foundation for the implementation of green investments. This also confirmed the conclusion that the coupled and coordinated high-value agglomeration region evolved towards the middle reaches of the Yangtze River. The deflection angle of the standard deviation ellipse fluctuated from 28.99° to 28.35°, with an overall shift in the "due north-south" direction, similar to the conclusion that the center of gravity shifted southward in the north-south direction, while the principal axis length of the standard deviation ellipse increased during the study period and the flattening of the ellipsoid decreased from 1.138 to 1.129,

indicating that the distribution of coupling coordination expanded during 2005 and 2019, and the degree of synergy between green investment and green ecology increased, but its fragmentation was inevitable. This may be due to the gradual improvement of the green financial system, and the level of green investment is also tilted by policy resources. The provinces can put the amount of green investment into relevant fields, which makes the degree of synergistic development of green investment and green ecology gradually rise. However, the convergent policy requirements also restrict the development of each province, making it difficult to form regional characteristics, and thus creating a fragmented situation.

The findings of the study show a more significant coupling effect between green investment and green ecology in China, at the level of temporal evolution analysis, spatial clustering analysis, and spatial pattern evolution analysis.

5 Conclusion and policy implications

The study focuses on the coupling coordination of green investment and green ecology in 30 Chinese provinces and cities from spatial and temporal dimensions using the coupling coordination model, kernel density estimation, spatial autocorrelation, and spatial standard deviation ellipse methods. The main findings of the study can be summarized as:

Overall, the study found that the coupling effect of green investment and green ecology in China is generally at a preliminary stage. In particular, the coupling coordination value of the green investment and green ecology is gradually increased, but the overall state is in a serious imbalance. Meanwhile, the regional gap of coupling coordination narrowed with the most significant variability in the eastern region. Specifically, the coupling coordination value of the green investment and green ecology in China developed from 0.143 to 0.231, but the coordination type is dominated by low-level coordination, while among all regions the difference coefficient in the eastern region is the highest.

The aggregation effect of the coupling coordination of green investment and green ecology is significant. The high-value aggregation area extends from the lower reaches of the Yangtze River to the middle reaches of the Yangtze River, while the western region is dominated by low-value aggregation. The specific performance of the significant high-high type and hot spot areas are from the Yangtze River estuary to the middle reaches of the Yangtze River transfer trend, but the western region such as Gansu has shown low-value aggregation characteristics. Therefore, it is suggested to highlight the dominant position of the Yangtze River Economic Belt, strengthen cooperation with neighboring regions, share green investment patterns and green ecological governance experience, and achieve the goal of coordinated development of green investment and green ecology in internationalized city clusters.

The degree of synergistic development between green investment and green ecology is increased, but fragmentation is inevitable. At the same time, the center of gravity of coupling coordination moved to the southwest, and the spatial pattern gradually weakened in the direction of "northeast-southwest." Moreover, the distribution range of the standard deviation ellipse is expanded and the flattened ellipsoid is decreased. The center of gravity of the coupling coordination value is shifted to the southwest in Henan, and the deflection angle is also fluctuated down.

It is suggested that China should continue to improve the green financial system, refine the investment scope of green finance, provide important policy support for the in-depth participation of green investment in the fields of green welfare, green economy, and natural resources, and actively guide the flow of social capital to green ecology. Therefore, it is recommended that Chinese provinces give full play to their geographical advantages, actively carry out the Northeast Revitalization Strategy and Belt and Road Development Strategy, and develop green ecological development strategies according to local conditions.

This paper finds a coupling effect between green investment and green ecology through a quantitative study of coupling characteristics, indicating that there is a degree of positive effect between green investment and green ecology in China. On the other hand, this paper finds that the center of gravity of the combination of green investment and green ecology is close to the middle reaches of the Yangtze River, which shows the excellence of the Yangtze River Economic Belt strategy and provides a regional model for realizing the synergistic development of green investment and green ecology. Due to the complexity of the facilitation between green investment and green ecosystem, this study conducted a macro empirical analysis on the coupling coordination between green investment and green ecology at the provincial level, and ignored at the city level. Moreover, the study did not find the influencing factors of coupling and coordination. The above deficiencies and weaknesses can be overcome in future studies to make more valuable research on green investment and green ecology.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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.

Publisher's note

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A configuration study on rural residents' willingness to participate in improving the rural living environment in less-developed areas—Evidence from six provinces of western China

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Maintaining the sustained improvement of human living environments in rural areas while improving habitats poses a substantial challenge. While promoting participation by rural residents is key to achieving the improvement of rural living environments, existing studies have mostly focused on the "net effect" single factors have on their participation. However, few studies have considered the combined effects of multiple characteristics in complex contexts. In this study, a revised model of planned behavior is constructed, based on configuration theory; the histories of pathways that influence rural households' willingness to participate in improving rural living environments are also explored. The perspective of concurrent causality is adopted, and this study examines whether a "mutual substitution effect" exists between the antecedent conditions in different paths. A questionnaire survey was conducted in six provinces (including autonomous regions) in less-developed areas of China. Six configuration paths of rural residents' higher willingness to participate in the improvement of rural living environments were obtained using fuzzy-set qualitative comparative analysis. The results show that: 1) In the path of high willingness to participate, the behavioral attitudes characterized by the "trustworthiness of village leaders" and "group identity" play the central role. "Social capital" and the "trustworthiness of village leaders" have a mutual substitution effect. 2) When using positive behavioral attitude evaluation as a core condition, "educational level" and "environmental awareness" have a mutual substitution effect. "Household income level", as the marginal condition, has a mutual substitution effect with "environmentally friendly habits". Therefore, to increase rural residents' willingness to participate in improving rural living environments in less-developed areas, the level of the "trustworthiness of village leaders" and "group identity" should be raised. In

addition, depending on the "mutual substitution effect" between different conditions, to achieve the same improvement in rural areas with a low level of "social capital", the focus should be on improving the "trustworthiness of village leaders". For rural areas with a slight difference in "household income level", the focus should be on promoting the formation of "environmentally friendly habits" among rural residents.

KEYWORDS

rural living environments, collective action, configuration theory, theory of planned behavior, China

1 Introduction

Efforts are being made worldwide to improve rural living environments, as these form an important part of human habitation (Peterman et al., 2013; The third United Nations Environment Assembly, 2017; Hu and Wang, 2020). According to the United Nations Commission on Population and Development, about 44% of the global population was still living in rural areas in 2020 (Shen et al., 2022). In the process of rapid urbanization, rural areas' economic development places those areas at a relative disadvantage. Thus, efforts to achieve economic development in rural areas have become a priority strategy in most regions. However, the improvement of rural living environments is often neglected in this process (Hu and Wang, 2020). Rural areas typically have a high concentration and abundance of natural resources, and in these areas, the relationship between humans and nature is close. If the rural living environment is protected, then to a large extent, the natural ecological environment is also protected. Therefore, maintaining a sustainable rural living environment in rural areas that are relatively underdeveloped has become a global and central challenge in the process of improving the natural environment (He et al., 2022). This challenge is even more severe in less-developed areas (Brister, 2016; Cooney et al., 2017). In China, most of the less-developed areas are also located in key national ecological function protection zones, and a large spatial overlap has been found between ecologically fragile areas and areas with low economic development. Incidentally, relatively less-developed rural areas in China generally also have low economic development; this leads to a prominent shortage of governance resources for the improvement of living environments in rural regions (Kramer et al., 2009). Therefore, the problems associated with rural living environments in China's less-developed regions actually present a microcosm of the contradictory problems between economic development and environmental improvement; problems faced by many of the world's less-developed regions.

The rural living environment is a typical commons, and therefore, promoting rural residents' participation in its improvement is a core path to effectively governing problems associated with rural living environments (Wang et al., 2021). Many studies have explored the willingness of rural residents to participate in improving their living environments. In terms of research objects, most studies have focused on a specific aspect of rural living environments, such as domestic waste treatment (Han et al., 2018; Han et al., 2019; Li et al., 2019) or domestic sewage treatment (Gu et al., 2016; Cheng et al., 2020). In terms of research methods, most studies have focused on quantitative analyses under a single causal mechanism (Wang et al., 2021), mainly exploring the "net effect" of single factors on outcomes (Ragin, 2000). Depending on the findings of these studies, the factors affecting rural residents' willingness to participate in improving their rural living environments were divided into external factors at the objective level and internal factors at the subjective level. In terms of objective-level influencing factors, the main factors are institutional incentives and constraints (Maryia et al., 2015), social norms (Sun et al., 2020), and information supply (Starr and Nicolson, 2015). In terms of the influencing factors of rural residents' subjective level, the main factors are environmental cognition (Sun, 2019), demographic characteristics (Miafodzyeva and Brandt, 2013), and transportation conditions (Liu and Huang, 2014).

Although existing studies have explored this topic from different perspectives, three specific areas merit further research. 1) Thus far, the factors that are influencing rural residents' willingness to participate in improving their living environments in less-developed areas have not been considered from the perspective of differences in local development. 2) Influencing factors have mostly been considered from a single aspect, and a discussion regarding the combined effect of multiple factors is missing so far. 3) Existing relevant studies that focus on the subjective attitudes of rural residents are inadequate, and their results should be supplemented. To this end, in this study, four provinces and two autonomous regions located in less-developed regions of China were selected, namely Yunnan, Gansu, Shanxi, Guizhou, Guangxi, and Ningxia. The paths of configurations that influence rural residents' willingness to participate in improving their living environments were explored from the perspective of configuration analysis. Two research questions were addressed (in order) to provide a reference basis for developing strategies aimed at improving local rural living environments in less-developed areas and developing countries. 1) Which factors combine to influence rural residents' willingness to participate in improving their

living environments in less-developed areas? 2) What combination of factors affects the willingness of rural residents in less-developed areas to participate in improving their living environments?

2 Theoretical foundations

2.1 Collective action theory

Rural residents are the most direct beneficiaries of improvements in the rural living environment; they are also the most important builders, maintainers, and supervisors in this process (Wang et al., 2021). Without the participation of rural residents, improving rural living environments would be difficult (Yu, 2019). Rural living environments are typical common pool resources, because rural residents cannot be excluded from using the environment at a low cost. Also, rural residents are more likely to discharge pollutants, such as domestic sewage, garbage, and farming manure, directly into the rural public environment, without facing restrictions. Such behavior damages the rural living environments and eventually causes rural living environments to suffer the "tragedy of the commons". Faced with this problem, Ostrom (1990) argued that collective action, *via* the participation of all users, is the best solution to the problem of the tragedy of the commons. The key to the formation of collective action lies in the participation of all users, together with the provision of clear principles and paths for the governance of the commons in rural living environments.

2.2 Theory of planned behavior (TPB)

The question of how farmers can participate in improving their rural living environments can be clarified by assessing the willingness of rural residents to do so. Ajzen's Theory of Planned Behavior (TPB) explores why individuals have specific intentions and how their meanings can be changed at the subjective level. The theory of planned behavior proposes that behavioral attitudes, subjective norms, and perceived behavioral control are the core elements determining individual choices and decisions (Ajzen, 1991, 2011). Attitudes are the positive or negative evaluations made by individuals when faced with a certain behavior. Subjective norms are the influences individuals face from other key individuals or groups around them, particularly regarding whether to adopt a certain behavior. Perceived behavioral control is the influence individuals perceive when displaying a certain behavior, which is referenced against past experiences and perceptions (Schwartz, 1992). Since its introduction, the TPB has been widely applied for studying individual behavioral intentions and problems with behavioral decisions. For example, Bagheri et al. (2021) applied the TPB to examine farmers' behaviors in using safe pesticides in Ardabil Province, Iran. Arunrat et al. (2017) applied the TPB to discuss farmers' intentions and decisions to adapt to climate change. The study proposed that the farmers' wishes directly influence their decision-making behavior. Sereenonchai and Arunrat (2022) combined the TPB with value-belief-norm (VBN), and the health belief model (HBM) presents a practical framework for communication that extends the flexibility of the TBP in practical research. Xu et al. (2022) used the TPB to construct a two-stage decision-making framework for contracting-renewal, as well as to determine how the process influences the formation of willingness. Vijaya and Ranja (2022) refined and applied an expanded TPB in their application of the TPB to study the factors influencing commuters' intentions to use public transport after the COVID-19 outbreak (Vijaya and Ranja, 2022).

2.3 Configuration theory

Configuration theory is based on "multiple concurrent causations", suggesting that paths leading to the same outcome may have multiple factors, i.e., different combinations and configurations of multiple factors result in equivalent paths (Meyer and Anne, 1993; Ragin, 2000, 2014; Fiss, 2007, Fiss, 2011). This theory provides systematic explanations for complex problems based on an integrated thinking and theory approach (Park et al., 2020). Configuration theory adopts a group perspective and a holistic analytical perspective. Initially based on Boolean logic employed to analyze the logical relationships that exist between antecedent conditions and outcome variables (Delery and Doty, 1996), rather than the "net effect" of a single variable, configuration theory focuses on holistic values that constitute the outcomes of social practices (Miller, 1986). The configuration theory research method differs from the traditional typo-logical test (Doty and Glick, 1994). However, configuration theory extended the application of the latter in terms of its theoretical explanation and has broader development and generalization prospects. For example, when comparing different pathways that lead to the same outcome, configuration theory makes it possible to explore whether the preconditions of various paths have a "mutual substitution effect". In other words, it is possible to explore whether one or more of the conditions that form a pathway can be substituted by other conditions, contributing to the same outcome. Thus, configuration theory provides viable theoretical guidance for the development of locally-adapted policies or practice strategies. In conclusion, the premise of configuration theory is to understand social phenomena as systems, to fully examine the combinatorial effects among conditional variables when exploring causal complexity, and to treat the combination of multiple conditional variables as concurrent causes constituting equivalent paths for the occurrence of outcomes (Adner, 2017; Du, 2021).

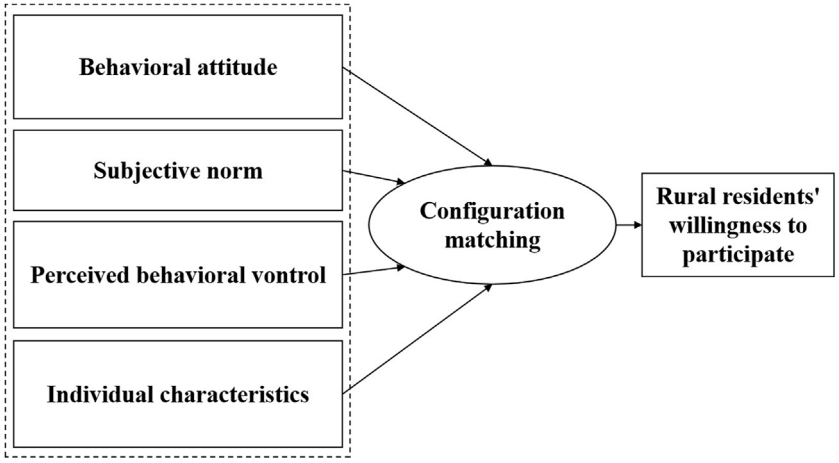

FIGURE 1
An improved model of planned behavior theory of rural residents' willingness to participate in the improvement of their living environment.

2.4 Analytical framework

Given that the destruction of rural living environments is a form of the tragedy of the commons with complex characteristics, the participation of rural residents is a key path to the governance and improvement of rural living environments. Therefore, an exploration of the factors that influence rural residents' willingness to participate in improving their living environments should be based on the complexity of the tragedy of the commons. On the one hand, based on the TPB, rural residents' willingness to participate may be simultaneously influenced by their behavioral attitudes, subjective norms, and perceived behavioral control. Moreover, individual characteristics of rural residents influence their willingness to participate in improving their living environments (Nan et al., 2011; Liu et al., 2019; Deng et al., 2021). On the other hand, to examine the concurrent effects of multiple variables on outcomes in complex situations, this paper combines the theory of configuration (which is applicable to studying multi-factor concurrent causation), with the TPB. Further, an extended TPB model is constructed (Figure 1) to examine the paths of histories that affect rural residents' willingness to participate in the improvement of their living environments.

2.4.1 Influence of behavioral attitudes on rural residents' willingness to participate

Behavioral attitudes are positive or negative evaluations individuals make when they are confronted with a particular behavior. When deciding whether to participate in actions to improve their living environments, rural residents will first evaluate whether such participation can produce expected benefits. Improving rural living environments is a typical public goods supply behavior, as the result of environmental improvement will benefit all rural residents. Under this premise, if rural residents identify with the village collective and are willing to suffer individual costs to achieve collective common good, they will be ready to participate. In other words, if they have a high level of group identity, they will see their participation in the collective action as a collective benefit (Klandermans, 2002). Conversely, rural residents do not perceive collective benefits as benefits generated by participating in collective action. Therefore, rural residents' "group identity" becomes the basis for evaluating their participation in improving their living environments. This group identity is also a component of their attitudes toward participating. At the same time, the collective action of improving the human living environment is carried out under the supervision of village leaders and cadres. Whether villagers participate in the action is still based on their evaluation of the benefits to be expected subjectively when participating in related activities. If rural residents believe that village leaders have high trustworthiness, they will believe that participation in the action will lead to expected benefits. Conversely, if rural residents believe that the trustworthiness of their village leaders is insufficient, they will believe that participation in relevant actions will not lead to expected benefits (Jia et al., 2019). Therefore, the trustworthiness of village leaders is a further basis for rural residents' evaluation of the behavior of participating in improving their living environments. In other words, the trustworthiness of village leaders is also a component of rural residents' behavioral attitudes when making decisions regarding their willingness to participate in the improvement of rural living environments (Zhao et al., 2016).

2.4.2 Influence of subjective norms on rural residents' willingness to participate

Subjective norms refer to the influence key individuals or groups impose on individuals regarding whether to adopt a specific behavior. In the context of improving rural living environments, rural residents are influenced by the affirmative and negative influences of surrounding groups or others within their village. This influence can have either a demonstration or supervisory effect on their participation decisions. The demonstration effect can be understood to be the effect of relatives and friends on rural residents' willingness to participate in actions to improve rural living environments. This effect will spread through rural social networks and promote farmers to imitate each other; the effect will either enhance their desire to participate, or conversely, reduce their willingness to participate (Chen et al., 2007). The monitoring effect suggests that rural residents' participation in collective action decisions is restricted by their "acquaintance" group, i.e., farmers may be excluded from the same rural social network because they hold different opinions. Thus, subjective norms in rural residents' willingness to participate in improving their living environments are mainly influenced by the social network norms of the collective surrounding them.

2.4.3 Influence of perceived behavioral control on rural residents' willingness to participate

Perceived behavioral control refers to the perception of individuals regarding the influence a specific behavior will have, based on their previous experience and cognition. In the context of this study, rural residents sense the impact of their participation in actions to improve their living environments through their level of environmental awareness. Their previously displayed environmentally friendly habits also impose a certain influence, as these are a form of behavioral experience (Dunlap et al., 2000). Generally, rural residents with high ecological cognition and sound environmental practices are more willing to participate in improving their rural living environments. The main reason is that perceived behavioral control promotes their willingness to participate. Still, rural residents' participation in improvement actions is a subjective decision-making problem in a complex situation that is inevitably and simultaneously influenced by other factors. Therefore, this decision-making problem should be explored through a more systematic and comprehensive analysis.

2.4.4 Influence of individual characteristics on rural residents' willingness to participate

The individual heterogeneity of rural residents' characteristics also affects their willingness to participate in improving their rural living environments (Wang et al., 2021). Among these characteristics, education level is a typical individual characteristic that can enhance the rationality of individual rural residents' decision-making (Han et al., 2021). Furthermore, based on quantitative analyses, it has been concluded that rural residents' education level significantly affects their willingness to participate in improving their living environments. However, a sufficient basis for determining the direction of their influence is still not available (Zhao et al., 2021). Household income level is an essential measure of rural residents' heterogeneity, especially their participation in providing rural public goods, making income level a crucial factor influencing rural residents' cost awareness (Van et al., 2021). The heterogeneity of residents' household income levels in rural areas, caused by the wide variation in agricultural resource endowments, results in different cost sensitivities. These affect rural residents' willingness to participate when making decisions about improving their living environments.

2.4.5 Framework for configuration analysis of rural residents' willingness to participate

Based on the above analysis, in this paper, behavioral attitudes are further allocated to the two dimensions of group identity and the trustworthiness of village leaders. Subjective norms are measured by social capital, and the two dimensions of environmentally friendly habits and environmental awareness are allocated to perceived behavioral control. The two dimensions of education level and household income level are allocated to rural residents' characteristics. Under full consideration of multiple factors influencing the results, an applied model of configuration analysis based on an improved TPB was constructed (Figure 2).

3 Data sources

The data for this study were obtained *via* a questionnaire survey, conducted from March to May 2021 in the six provinces (including autonomous regions) of Yunnan, Guangxi, Shanxi, Gansu, Ningxia, and Guizhou. Located in China's western region. The economic development level of China's western region lags behind that of the central and eastern regions, identifying this region as a typical underdeveloped region in China. The reasons why the above six provinces and autonomous regions were selected as survey subjects are summarized as follows: 1) All of the included provinces and autonomous regions belong to the less-developed regions of western China. 2) The population density of these provinces and autonomous regions is relatively higher than that of other western provinces in western China, which facilitates the acquisition of a sufficiently large sample. 3) Guangxi, Yunnan, and Guizhou belong to the southern region of China, while Ningxia, Shanxi, and Gansu belong to the northern region. Including both types of regions reduces the influence of the difference between the south and north of the sample in terms of geographical location. 4) The above six provinces and autonomous regions are richer in terms of rural natural

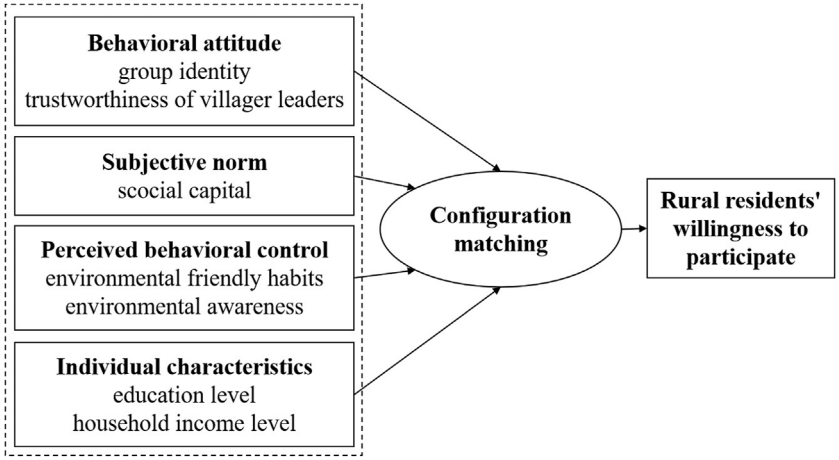

FIGURE 2
Applied model of rural residents' willingness to participate in the improvement of rural living environments subgroups based on an improved theory of planned behavior.

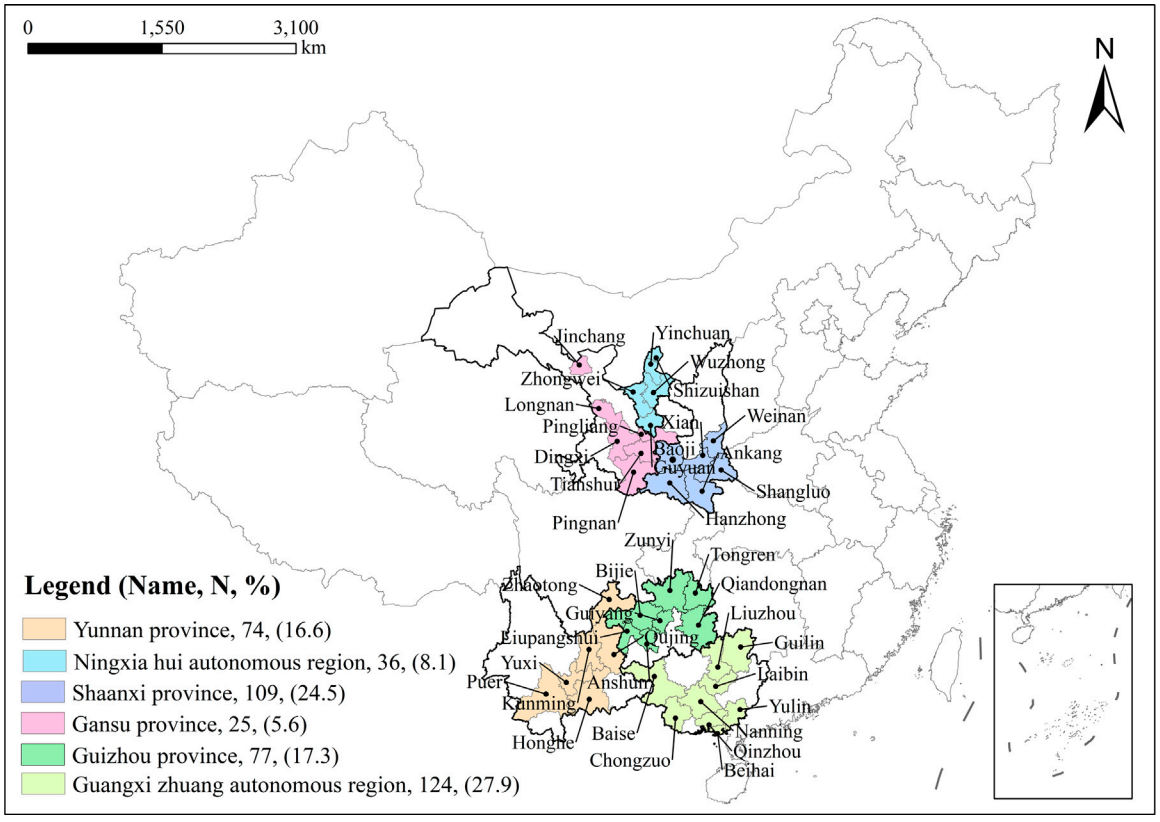

FIGURE 3
Geographical and quantitative distribution of samples.

environmental resources, compared with other western provinces, and their need for improved rural living environments is more urgent. Affected by the COVID-19 pandemic, this questionnaire survey was distributed *via* an online platform, and the sample was drawn by a combination of stratified and random sampling. According to differences in economic development and population size in the less-developed regions of China, the sample areas are located in the southern and northern regions of the geography of the less-developed regions of China (Figure 3). This location difference enables better control of the influence of the geographical variability between the north and south on the results.

Questionnaires in this study were distributed in the following ways: The research team first contacted the village cadres of the sample villages. With their consent, the village cadres were entrusted to issue the questionnaire to the villagers through the online platform. The village cadres were also asked to mobilize and encourage the villagers to fill in the questionnaire online. It should be noted that this way of asking respondents to fill out the questionnaire on line is prone to the problem of common method bias, which is a common problem with self-report questionnaires. The main reasons for this problem are consistency of motivation, implicit correlation bias, default tendency, mood state, and transient emotion. To overcome the common method bias problem, this study adopted the following two approaches in conducting the survey and in the data analysis process: first, at the beginning of the questionnaire, respondents were assured that the survey is anonymous and that their personal privacy information would be strictly protected. This meant respondents could fill in the survey with complete confidence and reduced speculation about the purpose of the study. Second, this study referred to Gao et al. (2016), Gao et al. (2015), and Jones et al. (2015) to find out how to improve the reliability of respondents' feedback in unsupervised subjective questionnaires. This paper set up several "trap questions" that were logically related to each other. The respondents' responses to the "trap questions" were used to determine whether the respondents had adverse reactions, intentionally provided useless information, and/or provided false information in the answering process. Those samples that failed the trap question were eventually eliminated, to minimize the impact of common methodology bias on the study, further improving the credibility of the data.

The questionnaire consisted of four parts, including basic information about the respondents, the implementation of habitat improvements in the village, the length of time respondents' families had lived in the region, and the data of each specific variable involved in this study. A total of 566 questionnaires were received; invalid questionnaires were identified according to the following items:

① More than 5% of questions were not answered.
② There are obvious logical errors in the answers.
③ The questionnaire results show clear regularity (e.g., continuous diagonal filling).
④ The time taken to complete the questionnaire was much shorter than the standard response time.

Finally, 445 questionnaires were identified as valid, and the overall efficiency of the questionnaire was 78.62%.

About the same number of male (50.3%) and female (49.7%) respondents participated in the survey. The distribution of respondents was relatively even across all ages, mainly concentrated in the 30–60 age group, which accounted for 63.1%. Respondents were primarily villagers who regularly reside in the village, with 48.9% living there for more than 10 months per year. A total of 68.5% of the sampled households own a residential site in town. Compared with data from China Statistical Yearbook 2021, the sample obtained for this study is consistent with the current rural reality in terms of the proportion of sexes, age groups, ownership of residential sites, and educational attainment. Therefore, the data are highly reliable and representative. In addition, the sampled rural residents are mainly long-term residents of rural areas and represent the prominent influence of improvement measures of rural living environments, ensuring the applicability of the data.

4 Data analysis methods

4.1 Fuzzy-set qualitative comparative analysis

Fuzzy-set qualitative comparative analysis (fsQCA) is a research method suitable for addressing multiple concurrent causations (Schneider and Wagemann, 2012). This method is based on a Boolean logic (ensemble) inference of outcomes, based on the conditional variable X and the outcome variable Y. Fuzzy-set qualitative comparative analysis treats causal explanations as configurations of factors, rather than as path effects of independent variables. The method is mainly based on the theory of configuration in practical operation and can be effectively applied to specific explored problems, based on the theory of configuration. Therefore, fsQCA is more suitable for exploring the various paths of rural residents' willingness to participate in improving their living environments. In the analysis process, condition and outcome variables are calibrated and transformed into sets. Then, a necessary condition analysis of a single condition variable is conducted to test whether a single condition variable constitutes an essential condition for the outcome variable. Finally, a sufficient condition analysis is conducted (Wagemann and Schneider, 2010), including a raw consistency threshold (*Consistency*), PRI (proportional reduction in inconsistency) thresholds, case frequency thresholds, and the combination of conditional

variables for the outcome occurrence, i.e., the grouping path, based on counterfactual thinking and Boolean minimization operations. According to Ilias and Arch (2021), a condition is considered necessary if that condition occurs at the time the outcome occurs, and is considered sufficient if a situation is observed in a case and the development occurs. Two leading indicators for assessing necessary and sufficient conditions are consistency and coverage. Consistency represents the degree of confidence associated with a combination of conditional variables producing a specific outcome. Consistency is calculated according to (Eq. 1):

$$\text{Consistency}\,(Y_i \le X_i) = \sum[\min(X_i, Y_i)] \Big/ \sum Y_i \qquad (1)$$

where, X_i denotes the degree of affiliation of the condition variable, and Y_i denotes the degree of association with the outcome variable. Generally, a single condition or combination of conditions with a consistency exceeding 0.8 is considered sufficient for the outcome variable.

The degree of coverage is the degree of case coverage that consistently occurs with a particular combination of dependent variables, and is expressed as the strength of the explanation of the variety of conditional variables for the outcome variable. Larger values of the coverage metric indicate that individual conditions and combinations of conditions explain the outcome better (Ragin, 2014). The degree of coverage is calculated according to (Eq. 2):

$$\text{Coverage}\,(X_i \le Y_i) = \sum[\min(X_i, Y_i)] \Big/ \sum Y_i \qquad (2)$$

where X_i and Y_i have the same meaning as above. The variable result of X_i has the value range of (0, 1); X_i includes seven conditional variables of education level, income level, environmental awareness, environmentally friendly habits, group identity, social capital, and trustworthiness of village leaders. Finally, Y_i is the ith household's willingness to participate in improving their rural living environments.

4.2 Description of variables

4.2.1 Outcome variables

The design of the outcome variables is based on official policy documents promulgated by the Chinese government and public news. For example, in the central government's policy document "Five-Year Action Plan for the Improvement and Upgrading of the Rural Living Environment (2021–2025)[1]", the core elements of improving rural living environments include the cleaning and management of public toilets, the management of rural domestic sewage, the management of household waste, and the beautification of villages' appearance. In implementing this policy, local governments further include the maintenance of village roads[2], the repair of irrigation channels[3], the organization of cultural and sporting activities[4], and the restoration of public places of action[5], such as ancestral halls. For these reasons, this study ultimately chose the eight indicators shown in Table 1 to measure the rural residents' willingness to participate in improving their living environments.

4.2.2 Conditional variables

The design of the "trustworthiness of village leaders" takes into account the fact that this study is based on a Chinese cultural context, and therefore adopts the Chinese government's indicators for cadre competency evaluation. These indicators include the five aspects of character, competence, initiative, output and integrity, a requirement that also comes from the official policy document, the "Regulations on the Assessment Work of Party and Government Leaders"[6].

The selection of "environmental awareness" was based on existing literature. Previous literature has found that farmers' environmental perceptions, such as their understanding of environmental hazards, as an internal factor, influence their pro-environmental behavior more than external constraints (Kotchen and Reiling, 2000). Farmers' perceptions of the environment in rural areas are mainly derived from their agricultural production and rural life processes. On the one hand, pesticides applied to control crop pests and diseases and the disposal of manure produced in livestock farming are essential aspects of farmers' participation in agricultural production. On the other hand, the use of water in daily life and the disposal of household waste are also actions that farmers have to take in their daily lives. Therefore, in designing the questionnaire, this study takes these four types of activities (that farmers must be exposed to in their production and living) and uses these activities to reflect the environmental awareness of farmers. This is achieved by examining their knowledge of the hazards of pesticide pollution, domestic sewage, domestic waste and livestock manure.

"Group identity", as a core psychological trait of group members, occupies an important place in collective action research (Tajfel and Turner, 1979; Tajfel, 1982). In addition, studies in the field of social psychology have demonstrated a high

1 Please see: http://www.gov.cn/zhengce/2021-12/05/content_5655984.htm.

2 Please see: https://www.163.com/dy/article/HIEE4BG50534B9UK.html.

3 Please see: https://new.qq.com/rain/a/20221122A016NG00.

4 Please see: https://baijiahao.baidu.com/s?id=1639298706999982237&wfr=spider&for=pc.

5 Please see: https://baijiahao.baidu.com/s?id=1702132352859358345&wfr=spider&for=pc.

6 Please see: http://www.gov.cn/zhengce/2019-04/21/content_5384955.htm.

TABLE 1 Indicator system of outcome and condition variables for rural residents' willingness to participate in improving their living environments.

Variable name	Measurement indicators
Willingness to participate	Would you be willing to work if the village needed help with the following tasks? 1 = very willing; 2 = willing; 3 = unable to say; 4 = not very willing; 5 = not at all willing
	Cleaning of sewage ditches
	Repairing damaged roads
	Repairing water irrigation canals
	Picking up rubbish in the village
	Beautifying the appearance of the village
	Organizing cultural and sports activities
	Managing and cleaning public toilets
	Repairing ancestral halls and temples
Trustworthiness of village leader	Please rate the competence of the village clerk in your village according to the statements below: 1 = strongly disagree; 2 = disagree; 3 = fairly agree; 4 = agree; 5 = strongly agree
	He does a lot of good for the people
	He is a fair and honest man
	He is a man of high moral character
	He is a very hard-working man
	He is a man of great ability at work
Environmental awareness	Do you know anything about the following specific hazards? 1 = not at all; 2 = not very much; 3 = fairly; 4 = a little; 5 = very much
	The dangers of pesticide pollution
	The risks of wastewater run-off
	Hazards of domestic waste
	Hazards of livestock manure
Group identity	Do you agree with the following? 1 = totally disagree; 2 = not agree; 3 = unable to say; 4 = agree; 5 = strongly agree
	I would be happy if a journalist reported my good deed
	I would be pleased if village officials praised my good deed
	I would be pleased if a person is publicly praised for a good deed
	I would be pleased if a person is publicly criticized for an evil deed
	I feel honored when someone praises my village
	A well-developed village means a well-developed me
Social capital	Please rate your opinion based on the actual situation in your village: 1 = totally disagree; 2 = not agree; 3 = unable to say; 4 = agree; 5 = strongly agree
	I have a lot of good friends in my village
	Most of the people in the village are trustworthy
	Most of the villagers are willing to help each other
	The relationships between villagers are harmonious and united
	I feel at home back in the village

(Continued on following page)

TABLE 1 (*Continued*) Indicator system of outcome and condition variables for rural residents' willingness to participate in improving their living environments.

Variable name	Measurement indicators
Environmentally friendly habits	Do you agree with the following comments about yourself? 1 = totally disagree; 2 = not agree; 3 = unable to say; 4 = agree; 5 = strongly agree
	I am a person who protects the environment
	I am a hygienic person
	I am a person who loves to do good things
Education level	Your education level is: 1 = primary school or below; 2 = junior high school; 3 = high school or secondary school; 4 = bachelor's or college; 5 = master's and above
Household income level	The household *per capita* disposable income rank: 1 = very low; 2 = moderately low; 3 = moderate; 4 = moderately high; 5 = very high

correlation between group identity and group members' willingness to participate or actual actions (Yin and Zhang, 2015). Rural China is a typical acquaintance society; therefore, individuals have a strong psychological need to gain a group identity. Based on this reality, this study selected indicators to measure group identity by referring to Shu's (2020) study.

"Social capital" has received extensive attention in the study of collective action and pro-environmental behaviour (Anderson et al., 2004; Leonard et al., 2010; Sanditov and Arora, 2016; Engbers and Rubin, 2018). Scholars also generally agree that mutual trust and communication among members can be an excellent way to facilitate cooperation between members, to achieve collective action (Dawes et al., 1977; Anderson et al., 2004). Therefore, in this study, the questionnaire was designed to measure social capital in three dimensions: social network (Song and He, 2021), social trust (Li and Ren, 2022) and social participation (Yang et al., 2022), also taking into account the Chinese cultural context and linguistic expressions.

"Environmentally friendly habits" are essentially a self-concept, which is often derived from personal norms, i.e., a self-expectation based on internalized values (Schwartz, 1977). It is believed that the mediating effect of subjective criteria on people's pro-environmental behavior is activated when they are aware of both the consequences of things and the need to take responsibility (Klöckner and Blöbaum, 2010; Lauper et al., 2016). Therefore, in this study, the questionnaire was designed to measure "personal hygiene" from a self-interested perspective, "passions for doing good" from an altruistic perspective, and "protecting the environment" from a neutral perspective. The three indicators were designed to measure environmental habits from an unbiased perspective.

"Education level" and "household income level" were chosen as indicators for individual characteristics. Zhu et al. (2021) and Zhao et al. (2021) pointed out that "education level" and "household income level" are essential factors influencing farmers' willingness to participate. Based on this, on the one hand, referring to Su et al.'s (2022) study, this paper uses the following terms to measure the education level of respondents in five subgroups: "primary school or below", "junior high school", "high school or secondary school", "bachelor's or college" and "master's and above". On the other hand, this study has developed a basis for classifying income levels. Specifically, in order to protect the privacy of farmers' income in the questionnaire, we designed a calculation formula of *per capita* household disposable income that only farmers could see. The surveyed farmers input their household income in 2021 to finally calculate the *per capita* household disposable income of the surveyed farmers in 2021. Then, the surveyed farmers selected their own income categories according to the calculation results and compared with the hierarchical comparison table of household *per capita* disposable income from China Statistical Yearbook (2021) we provided in the questionnaire: less than 5,000 yuan = very low; 5,001–10,000 yuan = moderately low; 10,001–15,000 yuan = moderate; 15,001–20000 yuan = moderately high; more than 20,000 yuan = very high. And thus, the five levels of the household income of the respondents were obtained. Detailed measures of the condition and outcome variables are presented in Table 1.

4.3 Standardization of variables

Based on the influence of behavioral attitudes, subjective norms and perceived behavioral control on rural residents' willingness to participate were constructed, based on the previous theoretical foundation. Behavioral perspectives were measured by indicators of group identity and the trustworthiness of village leaders. Social capital and household income level were used to measure subjective norms. Environmentally friendly habits, environmental awareness, and education level were used to measure perceived behavioral control. The entropy weighting method was used to calculate the combined scores of outcome variables and the

condition variables of each dimension. The entropy method is an objective weighting method that determines weights based on the correlation between indicators and the changes in internal sample data. This method avoids the subjective bias caused by human factors (Shen et al., 2022). The calculation process is as follows:

First, the data are standardized. Indicators are standardized according to the selected indicators, assuming that i is the i th rural household and there are n residents in total; j is the j th evaluation indicator and there are m evaluation indicators in total. The standardization formula for the evaluation indicators is shown in Eq. 3:

$$X_{ij} = \frac{x_{ij} - min\left\{x_j\right\}}{max\left\{x_j\right\} - min\left\{x_j\right\}}, (i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m) \tag{3}$$

where x_{ij} is the original value of the j th evaluation indicator for the i th resident, X_{ij} is the value after standardization, $max\left\{x_j\right\}$ is the maximum value of indicator j, and $min\left\{x_j\right\}$ is the minimum value of indicator j.

Second, calculate the entropy value E_j of indicator j:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}},\ among\ them:\ X_{ij} \geq 0,\ and \sum_{i=1}^{n} X_{ij} > 0. \tag{4}$$

$$E_j = -k\sum_{i=1}^{m} P_{ij} \ln P_{ij},\ among\ them:\ k = \frac{1}{\ln(n)} > 0,\ E_j > 0. \tag{5}$$

Third, calculate the coefficient of variation of indicator x_j, $G_j = 1 - E_j$. A higher G_j means that more emphasis should be placed on this indicator.

Fourth, calculate the weights of indicator x_j, $W_j = \frac{G_j}{\sum_{i=1}^{m} G_j}$, where W_j is the weighting factor after normalization.

Fifth, the overall evaluation score, $S_j = \sum_{j=1}^{n} W_j x_{ij}$ is calculated *via* weighted linear summation. The composite score S_j ranges from 0 to 1, with higher scores indicating higher levels of the impact of the indicator.

4.4 Consistency tests and calibration of variables

Cronbach's reliability coefficient was used to test the consistency of the questionnaire. The results show that the Cronbach's alpha coefficient values for each condition dimension ranged from 0.838 to 0.954, indicating that the questionnaire has high reliability and good internal consistency. Regarding the validity of the questionnaire, the KMO value was 0.874, and Bartlett's spherical test approximate chi-square value was 10305.328, with a p-value of 0.000, reaching the significance level. Except for the two dimensions of education level and income level, all remaining variables were extracted by applying principal component analysis and the maximum variance rotation method. Six factors were obtained, all had eigenvalues larger than 1, and the cumulative variance contribution rate was 71.342%, excluding questions with factor loadings below 0.5. The measurement dimensions of conditional variables were obtained. The factors of the questions in each size were in the loading range of 0.551–0.898, indicating that the validity of the questionnaire is high.

According to the calculation logic of the fsQCA method, the set of conditional and outcome variables are first affiliated, and the values of calibrated variable will be affiliated between 0 and 1. Given the characteristics of the variables used in this paper (Ragin, 2000), the direct calibration method was used and 0.95 was set as a fully-affiliated calibration point, 0.05 as a fully unaffiliated calibration point, and 0.5 as a cross-calibration point. A value of 0.001 was added to results with a calibrated affiliation value of 0.5, in order to eliminate the problem that occurs when samples are not analyzed because they cannot be categorized (Ilias and Arch, 2021). The calibration results and descriptive statistical characteristics of conditional and outcome variables are presented in Table 2.

5 Results and analysis

5.1 Group path analysis of rural residents' willingness to participate

In the univariate analysis of necessary conditions, the values of the consistency indicators for each condition variable were less than 0.9. This result indicates that none of the single condition variables can constitute a high *versus* non-high level of rural residents' willingness to participate in improving their living environments. Multiple condition combinations are therefore needed to analyze rural residents' willingness to participate in a grouped manner. In the analysis, the minimum acceptable observational consistency has been set to 0.8, and the PRI threshold has been set to 0.75, with reference to Ragin (2004). As the sample size used in this paper is medium to large, the minimum acceptable observation frequency was set to 2 (Fiss, 2011; Ilias et al., 2016). The results of the calculations are presented in Table 3. Six paths were obtained in which residents have a high willingness to participate in improving their rural living environments. In addition, the consistency of the individual and overall solutions of the six configuration paths was greater than 0.75, meeting the requirements of grouping analysis. The level of consistency of the overall solution indicates the extent to which histogram paths can explain the results. For example, the overall character of 0.910 for higher willingness to participate demonstrates that the general approach can explain 91% of the high level of the sampled residents' participation. The overall coverage level indicates the level of case coverage by pathways. For example, a general coverage level of 0.611 for a

TABLE 2 Calibration results and descriptive statistical characteristics of conditional and outcome variables.

Variable name	Calibration breakpoints			Descriptive statistics			
	Full-set non-membership	Intermediate-set membership	Full-set membership	Mean	Std. Dev	Min	Max
Willingness to participate	3.048	4.000	5.000	4.009	0.564	1.556	5.000
Trustworthiness of village leaders	2.782	4.000	5.000	3.786	0.791	1.000	5.000
Environmental awareness	2.000	4.000	5.000	3.685	1.000	1.000	5.000
Group identity	2.761	4.000	5.000	3.920	0.637	1.000	5.000
Social capital	3.000	4.000	5.000	3.960	0.522	1.000	5.000
Environmentally friendly habits	3.000	4.000	5.000	4.042	0.639	1.000	5.000
Education level	1.000	2.000	4.000	2.350	1.200	1.000	5.000
Household income level	1.000	2.000	4.000	2.390	0.897	1.000	4.000

TABLE 3 Paths of high-level willingness grouping of rural households to participate in improving their living environments.

Configuration	Solution					
	H1			H2		H3
	H1a	H1b	H1c	H2a	H2b	
Social capital			●	•	•	●
Environmentally friendly habitsact		•	•			●
Household income level	•			⊗	⊗	●
Education level	●	●	●	●	⊗	●
Environmental awareness	●	●	●	⊗	●	
Trustworthiness of village leaders	●	●		●	●	●
Group identity	●	●	●	●	●	●
Consistency	0.942	0.945	0.929	0.952	0.937	0.947
Raw coverage	0.330	0.375	0.401	0.251	0.325	0.325
Unique coverage	0.017	0.001	0.031	0.032	0.128	0.022
Overall solution consistency	0.910					
Overall solution coverage	0.611					

Black filled circles (●) indicate the presence of a condition, and circles with an "x" (⊗) indicate the absence of that condition. Large circles indicate core conditions; small circles indicate peripheral conditions. Blank spaces indicate "don't care".

higher willingness to participate demonstrates that the six histogram pathways explain 61.1% of the sample having a high willingness to participate.

Configuration H1a shows that, with behavioral attitudes represented by group identity and the trustworthiness of village leaders, core conditions represented by environmental awareness and education level, and marginal conditions represented by higher household income levels, rural residents generate higher levels of willingness to participate. This path can explain 33% of the sample having higher levels of willingness to participate. Also, H1b indicates that residents have a higher level of willingness to participate when the core conditions are behavioral attitudes represented by group identity and the trustworthiness of village leaders, environmental awareness, and education level, as well as subjective norms, represented by environmentally friendly habits. A total of 37.5% of the sample

having a higher level of willingness to participate can be explained by this pathway. In addition, H1c indicates that, in the case of differences in behavioral attitudes in terms of the trustworthiness of village leaders, rural residents perceive a higher social capital. When subjective norms are represented by environmental awareness and education, which complement environmentally friendly habits, playing the central conditional role, residents will have a higher level of willingness to participate. A total of 40.1% of samples having a higher level of willingness to participate can be explained by this path. Then, H2a indicates that in the case of a low level of household income and a relatively low level of environmental awareness, group identity and trustworthiness of village leaders represented by behavioral attitudes, and educational attainment represented by trustworthiness as core conditions, supplemented by relatively high social capital as marginal condition, farmers will generate higher levels of willingness to participate. A total of 25.1% of the sample with higher levels of willingness to participate can be explained by this path. Then, H2b indicates that, from the perspective of household income level and relatively low education level, with behavioral attitudes represented by group identity and trustworthiness of village leaders, environmental awareness as a core condition, supplemented by relatively high social capital as a marginal condition, residents will generate higher levels of willingness to participate. A total of 32.5% of the sample having with higher levels of willingness to participate can be explained by this path. Finally, H3 indicates that, with behavioral attitudes represented by group identity and trustworthiness of village leaders, subjective norms represented by social capital, and individual characteristics represented by education level and household income level, 32.5% of residents having higher levels of willingness to participate can be explained by this path.

5.2 Overall comparative analysis of group paths

Comparing all six paths through which residents are highly willing to participate in the improvement of their rural living environments shows that the core conditions of group identity and trustworthiness of village leaders appear in five paths, but not in H1c. Path H1c has a substitution effect, with social capital as the core condition, in the absence of the core condition of the trustworthiness of village leaders. The main reasons for this result are summarized as follows: First, rural residents' group identity (expressed as their perception of collective identity, their psychological sense of belonging to the village collaborative organization, and their identity with the shared value beliefs of the village collective organization) is a crucial variable influencing the residents' participation in improving rural living environments through emotional effects (Qing et al., 2022). The group identity of rural residents is a centralized expression of their behavioral attitudes. Therefore, rural residents' group identity plays an essential role in influencing their willingness to participate in the collective action of improving their living environments. Second, Stern and Putnam (1994) pointed out that the level of political trust helps to increase the cooperation of the policy target group. The confidence rural residents have in their village leaders determines how they evaluate the actions suggested by those village leaders.

To a certain extent, the trust dimension embedded in social capital can act as a substitute for the lack of trustworthiness of village leaders, thus creating a substitution effect in the promotion of rural residents' willingness to participate in the governance of rural living environments. In conclusion, group identity and the trustworthiness of village leaders represent rural residents' behavioral attitudes, which are the result of rural residents' evaluation of collective action in their living environments. Rural residents' behavioral attitudes are fundamental subjective indicators determining their willingness to participate.

5.3 Grouping and intra-group comparison analysis of configuration paths

Based on the characteristics of the six configurations of residents with higher levels of willingness to participate, they can be grouped into three configurations: 1) The high level of perceived behavioral control path with positive behavioral attitude evaluation (H1); 2) the complementary path of subjective norm and perceived behavioral control with positive behavioral attitude evaluation (H2), and 3) the path of positive behavioral attitude evaluation and high level of personal criteria (H3).

(1) Perceived behavioral control path under positive behavioral attitude evaluation (H1)

Because of the presence of the trust dimension of social capital in H1c, this path could act as a substitute for the absence of the trustworthiness condition of village leaders and thus play the same role as the core condition of behavioral attitudes in H1a and H1b. Among these paths, household income level in path H1a has a substitution utility with environmentally friendly habits in paths H1b and H1c. In other words, in the absence of the marginal condition of environmentally friendly habits, the household income level plays the same role as a borderline condition. Therefore, the configuration of the three factors can be grouped into the same pathways that affect rural residents' willingness to participate at a higher level. In this category, rural residents' trust in village collective organization and village leaders leads to positive evaluations of actions that improve rural living environments. Higher levels of education and environmental awareness increase rural residents'

perceptions of positive outcomes of their participation in improvement actions. They also become more aware of the positive impacts of participating in improving rural living environments, complementing environmentally friendly habits or household income levels as marginal condition. The combined result is a high level of willingness to participate in improving rural living environments.

(2) Complementary pathways of subjective norms and perceived behavioral control under positive behavioral attitude evaluation (H2)

On the one hand, comparing the pathways of H2a and H2b in path H2 (with positive behavioral attitude evaluation as the core condition and other conditions unchanged), the two disorders of educational attainment and environmental cognition show a mutual substitution effect. In other words, the H2a combination of conditions had a lower level of environmental awareness as a marginal condition and a higher level of educational attainment as a borderline condition. In contrast, both paths induce willingness to participate in the H2b combination of the marginal state of low education and the marginal condition of heightened environmental awareness. On the other hand, lower household income is the common core condition in both H2a and H2b, which can be explained by the fact that residents with lower household income levels still show higher levels of willingness to participate, despite several other conditions. From a "cost-benefit" perspective in terms of the supply of public goods, this finding suggests that the main cause for these two results is that residents with higher household income levels are more willing to participate in collective action (Sulemana, 2016; Sarah, 2019). However, from a group-theory perspective, residents with lower household income levels are still influenced by the demonstration and monitoring effects caused by the combination of higher social capital stock and positive behavioral attitudes. This improves their evaluation of the expected benefits when participating in collective actions and eliminates the cost concerns in their decision to participate. Thus, a higher level of willingness to participate is generated.

(3) Positive behavioral attitudes and high level of subjective norms path (H3)

The path H3 is independent; i.e., residents show a high willingness to participate because of their positive behavioral attitudes, relatively high levels of education and household income, environmentally friendly habits, and high levels of social capital as core conditions. The suggested reasons for this result are summarized as follows: Rural residents' more positive evaluation of their participation behavior enables them to correctly judge the expected benefits of participating in improving their rural living environments. Higher levels of education and household income reduce the impact of participation costs on residents. Higher stocks of social capital let residents consider the evaluation of others more, thus acting as a specific constraint and a promotor of environmentally friendly habits. Overall, this path increases rural residents' perceptions of and demand for improvements in their environments, and the combination of these factors increases their willingness to participate in relevant actions.

5.4 Robustness tests

In this paper, the robustness of configuration results is tested by adjusting both the frequency threshold and the PRI threshold (Schneider and Wagemann, 2012). With an adjusted frequency threshold of 3, the configuration paths changed slightly and were mainly concentrated around the edge conditions. The total consistency and coverage changed only slightly, compared with the previous results. The absolute texture improved from 0.910194 to 0.918084, which is well above the minimum acceptable level. After adjusting the PRI threshold to 0.80 (while keeping the frequency threshold at 2), the group paths changed slightly, again concentrating around the edge conditions. The overall consistency and coverage were 0.925537 and 0.554631, respectively, both exceeding acceptable levels. Overall, the robustness of the study results is good.

6 Discussion

6.1 Configuration of factors influencing rural residents' willingness to participate

Rural residents' participation exerts an essential impact on the effectiveness of improvements to rural living environments. This is especially the case in less-developed areas, where the funds available for investments are limited and any actions are more dependent on collective participation by rural residents. For this reason, there is a need to effectively explore the factors that influence rural residents' willingness to participate (Daniel et al., 2021). Because of the requirement for control variables, studies using quantitative analysis methods often cannot integrate the synergies between different factors and are therefore more likely to identify a linear effect of a single variable (Xue et al., 2021). In this case, the findings are also difficult to apply to rural areas with different natural and social conditions. However, the qualitative comparative analysis approach considers the combined effect of various potential factors, eliminates the inhibiting effect of control variables in the quantitative method, and provides a more realistic picture of the studied problem. The results presented in this paper show that the willingness of rural residents to participate in improving

their living environments is not a linearly-correlated issue (Liu and Gong, 2022). Rather, this willingness is a multi-factor concurrent causality in a complex scenario. In other words, different configurations of factors can have the same impact on the willingness to participate.

6.2 Substitution effects exist between different influencing factors

This study identifies a substitution effect between different factors that influence rural residents' willingness to participate in improving their living environments. Among these factors, the behavioral attitudes characterized by the trustworthiness of village leaders and group identity play a core role in different path groupings. A core substitution effect exists between the two factors of social capital and the trustworthiness of village leaders; i.e., trust in social capital has the same role as the trustworthiness of village leaders (Mongoljin et al., 2021). Under the core condition of positive behavioral attitude evaluation (leaving other conditions unchanged), there is a mutual substitution effect between education level and environmental awareness. A substitution effect also exists between education, environmental awareness, household income, and environmentally friendly habits. Because rural areas in less-developed regions have different resource endowments and social conditions (Wu et al., 2022), it will be challenging to enhance rural residents' willingness to participate in improving their living environments through the same path. This makes the formulation of strategies in practice and local policy formulation challenging (Wang, 2019). In this paper, a variety of pathways is identified, all of which influence rural residents' participation in improving their living environments. These paths demonstrate the substitution effects among various influencing factors in different paths, which can provide theoretical guidance for local adaptation in the process of increasing rural residents' willingness to participate in governance in rural areas with varying natural and social conditions. For example, in rural areas with similar conditions (e.g., paths H2a and H2b in Table 1), but where the level of residents' education is relatively low, efforts should be made to increase the level of residents' environmental awareness. This can be achieved by increasing the dissemination of knowledge about improvements in human living environment, thus achieving the effect of increasing the willingness of farmers to participate in relevant actions.

6.3 The different pathways influencing farmers' willingness to participate provide a basis for tailor-made institutional design

Improving rural living environments is a complex and systematic project, and farmers, as the main users of rural living environments as a public good, are also the core participants in rural living environment governance. Therefore, in the process of rural living environment improvement, the interaction between the government's "top-down" policies and the rural residents' "bottom-up" autonomy is the key to successful governance (Zhu et al., 2022). A multifactorial exploration of farmers' willingness to participate in rural living environment improvements can provide insights into the various factors that influence farmers' willingness to participate in different contexts and the intrinsic linkages between other factors. This research can also provide a basis for governments to formulate policies that are tailored to local conditions. For example, in the less-economically developed regions of western China, the relatively complex geographical features have led to the formation of unique customs and practices in the rural areas of those different geographical regions. On the one hand, this leads to differences in the factors that influence farmers' willingness to participate in improving rural living environments. On the other hand, local authorities must consider regional cultural differences when implementing policies related to rural living environment improvement; this must be done at higher levels of government. At the same time, policy implementers also need to adopt policy implementation strategies that are more in line with local practices, according to the different cultural differences. This would help to ensure the effective implementation of national policies.

7 Conclusion and policy implications

The results of this study show that a combination of factors influences the willingness of rural residents to participate in improving their living environments. Rural areas in less-developed areas, with relatively low economic and social development levels, face certain shortcomings when carrying out relevant improvements. In this paper, the factors that influence rural residents' willingness to participate are examined in less-developed areas; six provinces in western China are taken as the sample. Existing research has mostly adopted quantitative analysis methods to explore single variables affecting rural residents' willingness to participate in improving their living environments, while controlling for certain potential variables. This paper adopts the configuration theory, which posits that synergistic interaction exists between the various possible variables that affect rural residents' willingness to participate. Further, the combination of different variables can generate a configuration path that affects rural residents' willingness to participate, which compensates for the suppression of potential variables by the single-variable approach. In addition, different path groupings can provide a realistic basis for implementing improvement strategies in less-developed areas, according to local conditions.

The policy implications of this study are threefold. First, the credibility and group identity of rural village officials should be enhanced, to improve the behavioral attitudes of rural households in less-developed areas toward participating in collective action and to increase their willingness to participate. On the one hand, the decision-making power of rural residents in the election of village cadres should be emphasized, in order to increase the trust of rural residents in their village cadres from the start. On the other hand, the links between village cadres and villagers, and between different villagers, should be strengthened, especially regarding issues of a public nature in rural areas. This will strengthen the villagers' sense of participation, and help to improve the group identity of rural residents. Second, various publicity and education activities regarding the rural living environment should be carried out to increase environmental awareness among farmers. For example, the benefits of environmental protection and the dangers of environmental damage in the village should be publicized at meetings or in the village's WeChat group. Third, various types of rural public environmental protection systems should be developed, to restrain villagers from damaging the environment and to promote the formation of environmentally friendly habits among residents. For example, individual environmental protection initiatives should be incorporated into village rules and regulations, and individual environmental protection recognition activities should be regularly carried out for all residents of the village.

This paper also has limitations. Because of the impact of COVID-19, the data do not cover all provinces located in the less-developed regions of China, thus preventing a comparative analysis with data from the relatively developed areas of the Middle East. Future studies can further incorporate geographical heterogeneity to obtain more comprehensive data, which could be used to explore the pathways of rural residents' willingness to participate in improving their living environments. Comparisons could be made between different regions by combining geographical heterogeneity. At the same time, due to the limited sample size obtained by this study, it is difficult to fully take into account more indicators of individual characteristics, such as gender, age and household size. Future studies need to find ways to obtain more samples, in order to verify more combination paths that affect the outcome variables. This would provide a more comprehensive basis for the continued promotion of initiatives to improve rural living environments in less-developed areas and other developing countries.

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

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. YS: Conceptualization, and manuscript; YQ and QS: Manuscript editing and manuscript review; QS, YS, and ZL: Manuscript review; YS, YQ, and YX: Methodology and manuscript 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.

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Pricing and coordination in a green supply chain with a risk-averse manufacturer under the reference price effect

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This paper considers a green supply chain using manufacturers and retailers as the research objects. The pricing and coordination strategy of the green supply chain, considering a risk-averse manufacturer, is investigated under the reference price effect. We establish centralized, decentralized, and cost-sharing contract decision-making models and then provide the optimal balancing strategy for each model. Further, we analyzed the optimal equilibrium strategy of different models. In the end, validate them through numerical simulation. We have found that the cost-sharing contract model is better than the decentralized decision model. Besides, manufacturers' degree of risk avoidance affects the wholesale price, product greenness, retail prices, and profits of supply chain members. It is verified that the cost-sharing contract can coordinate the supply chain system to increase the profit of members of the supply chain.

KEYWORDS

risk aversion, reference price effect, cost-sharing contract, green supply chain, pricing and coordination

Introduction

In recent years, consumer awareness of the environment has increased worldwide, and corresponding laws and regulations have been improved (Shen et al., 2013). Consumers often consider the level of the greenness of products when purchasing them, and the stronger the environmental awareness of consumers, the stronger their willingness to pay for green products. Based on the influence of environmental awareness, different scholars have proposed the concept of a green supply chain (Nagel, 2000; Sarkis, 2012; Fahimnia et al., 2015). From a business and leadership viewpoint, Nagel (2000) investigated the applicability of environmental supply chain management and green purchasing to supply chains and concluded that green purchasing would predominate in green supply chains. While previous researchers have frequently used the term "industrial environmental management" to describe green supply chains, Sarkis (2012) completed a review of related literature, redefined the concept's parameters, and offered a framework for future research in the field. Fahimnia et al. (2015) used bibliometric tools and a network topology map approach to analyze the green supply chain research area, identify current and potential future research directions, and provide specific green supply chain research lines. The earliest research on green supply chains can be traced back to 1996 at Michigan State University (Corbett and Klassen, 2006).

Currently, green supply chains have been widely researched, and most scholars focus on two aspects of green supply chain research: product pricing and coordination mechanism design. On green supply chain product pricing, Heydari (2020) investigates the issue from the perspective of customer environmental awareness for a green supply chain made up of a

TABLE 1 Related works.

Related paper	Green tech	Channel	Game theory	Coordination	Member behavior	Reference price effect
Wang et al. (2020)	Yes	dual	Stackel	No	No	Yes
Mondal et al. (2020)	Yes	dual	Nash/Stackel	No	No	No
Ghosh and Shah (2015)	Yes	single	Stackel	Yes	No	No
Taleizadeh et al. (2020)	Yes	single	Stackel	Yes	No	No
Shen (2021)	Yes	single	Stackel	Yes	No	No
Xu and Liu (2017)	No	single	Stackel	No	No	Yes
Wang et al. (2021)	No	dual	Stackel	No	No	Yes
Liu et al. (2016)	Yes	dual	Stackel	No	Yes	No
Xiao and Yang (2008)	No	single	Stackel	No	Yes	No
Li et al. (2017)	No	dual	Stackel	No	Yes	No
Bai et al. (2020)	Yes	single	Stackel	Yes	Yes	No
This research	Yes	single	Stackel	Yes	Yes	Yes

single manufacturer and retailer. Li et al. (2021) study the pricing strategy of a green supply chain consisting of two competing retailers and one manufacturer. From the perspectives of channel competition, government subsidies, and uncertain market demand, some researchers have studied the optimal product price problems in green supply chains (Li et al., 2016; Rahmani and Yavari, 2018; Lou et al., 2020; Yao and Shao, 2022; Yang and Xiao, 2017). Furthermore, some researchers have created manufacturer-direct sales channels based on traditional retail channels to investigate pricing issues in green supply chains. For example, Wang et al. (2020) consider a closed-loop green supply chain product pricing problem using a dual channel of the manufacturer's direct sales channel and retail channel, considering consumer-customized products. Mondal et al. (2020) examine pricing and greening strategies under three decentralized scenarios, including manufacturer-led, retailer-led, and Nash equilibrium, for a dual-channel green supply chain with forward and reverse manufacturer's channel and retail channel. A manufacturer-direct and retailer channels are used in a dual-channel sales model by Wang and Sun (2019) to explore static and dynamic wholesale pricing strategies in a green supply chain.

On the green supply chain coordination mechanism, unlike traditional supply chains, green supply chains focus on improving the greenness level of products and adopt various coordination contracts such as cost-sharing contracts, two-part price contracts, and benefit-sharing contracts to compensate manufacturers for their investment in the greenness level of products (Ghosh and Shah, 2015; Panja and Mondal, 2019; Yi et al., 2021), to coordinate the supply chain system and thus improve the profits of supply chain members. In a green supply chain coordination problem, Ghosh and Shah (2015) compare the effects of the cost-sharing contract and the retailer-manufacturer bargain on the cost-sharing contract on product greenness, green product price, and supply chain member profitability. In a two-level green supply chain with a manufacturer and a retailer, Taleizadeh et al. (2020) investigate the impacts of the cost-sharing contract and the repayment agreement on supply chain manufacturing and sales. Yang and Gong (2021) investigate the best supply chain decision-making under cost-sharing contracts by including retailers' reciprocal preferences in a green supply chain. Our study uses cost-sharing contracts to coordinate green supply chain systems, similar to the scholars mentioned above. In addition to the cost-sharing contract, some researchers use a two-part price contract to coordinate green supply chains (Li et al., 2016; Zhang et al., 2017; Sant, 2022). Revenue-sharing contracts are also often used to coordinate green supply chain systems. Panja and Mondal (2019) consider a two-level green supply chain consisting of manufacturers and retailers and find that revenue-sharing contracts can increase manufacturer and retailer profits by comparing optimal supply chain decisions under three scenarios: centralized, decentralized, and revenue-sharing. Shen (2021) introduces uncertain market demand, uses a revenue-sharing pact to coordinate the supply chain system based on a two-level green supply chain, and shows that the contract can improve greenness and reduce retail prices. A revenue-sharing contract is used by Yang et al. (2020) to coordinate a cartel supply chain while adding uncertainty to the manufacturer's product development environment.

The product's greenness influences consumer purchases, and in addition, consumer behavioral factors play an essential role in decision-making. In fact, consumers are influenced by the prices of similar products in other channels when purchasing goods, i.e., the reference price effect. Some scholars use the reference price effect when describing consumer behavior characteristics and incorporate it into the study of supply chain pricing issues. Based on the study by Xu and Liu (2017), it is found that in the closed-loop supply chain decision problem considering the reference price effect, as the reference price increases, the profits of manufacturers and retailers decrease, and the profits of third parties increase. Further, Malekian and Rasti-Barzoki (2019) explore the impact of price and advertising promotions on the profits of supply chain members under the reference price effect. Unlike the above studies, Wang et al. (2021) investigated the issue of channel supply chain pricing strategies for two

TABLE 2 Relevant parameter symbols.

Meaning	Parameters	Meaning	Parameters
Unit product cost	c	Degree of manufacturer's risk aversion	R
Wholesale price, decision variable	w	Retailer profit function	π_r
Retail price, decision variable	p	Manufacturer profit function	π_m
Market demand	d	Total profit function	π_{sc}
Product greenness, decision variable	θ	Retailer utility function	U_r
Green input costs of manufacturers	$c(\theta)$	Manufacturer utility function	U_m
Consumers' unit reference prices for green products	r	Total utility function	U_{sc}

different structures of online and offline channels under the reference price effect.

In past studies, researchers have considered the issue of supply chain pricing strategies when consumers have reference price effects. However, green supply chains operate in a process where decision-makers are not entirely rational. Behavioral economics studies have shown that the psychological factors of decision-makers influence the decision-making process and lead to deviations between results and reality. For example, supply chain members adopt a more conservative strategy, i.e., risk aversion. The risk-aversion behavior of supply chain members affects the decision-making of the supply chain system. Researchers have considered risk-averse supply chain pricing strategies (Liu et al., 2016); other researchers investigate the impact of risk aversion on pricing and supply chain coordination from the perspectives of demand uncertainty and asymmetric information (Xiao and Yang, 2008; Li et al., 2017; Alamdar et al., 2019; Bai et al., 2020).

From the above literature, it can be seen that the reference price effect on consumers is an important research area in the current green supply chain. In fact, manufacturers frequently exhibit risk-aversion behavior when developing green products, which impacts the optimal supply chain decision. In summary, this paper combines the two to study the problem of green supply chain pricing and coordination, considering manufacturers' risk aversion and reference price effects. Researchers investigated green supply chains under the supply chain members' risk-averse behavior but neglected to consider the reference price effect (Liu et al., 2016; Li et al., 2017; Bai et al., 2020). Another group of scholars considered the green supply chain under reference prices but did not consider the supply chain members' behavioral factors (Xu and Liu, 2017; Wang et al., 2021). However, we are clear that the pricing of products from the green supply chain is affected by both the reference price effect and the members' risk-averse behavior. Further investigation into the pricing and coordination of the green supply chain, taking into account manufacturers' risk-averse behavior under the reference price effect, could contribute to solutions for the collaboration of supply chain members.

In this paper, we make the following contributions: First, based on the research already mentioned, we further investigate how supply chain members optimize profits by taking manufacturer risk aversion into account under the reference price effect. Investigate the patterns of parameters such as product greenness, retail pricing, and wholesale pricing that are affected by the level of manufacturer risk aversion. Second, we also propose improved coordination methods, using cost-sharing contracts to increase the overall profit of the green supply chain and the profit of each member, as well as to increase the level of product greenness. Finally, we compare and analyze the optimal decision-making in each of the three models of decision-making: centralized, decentralized, and cost-sharing. Moreover, verify by numerical experiments to provide some management insights for the green supply chain. Table 1 clearly shows the contribution of this paper and some related works.

Table 1 lists the research gaps between this paper and other related works. "Green tech" indicates whether or not the research uses green technology. This paper investigated a green supply chain, where manufacturers invest in green product costs. "Channel" denotes whether the supply chain has only one channel. This paper is about a two-level supply chain consisting of a manufacturer and a retailer. Other scholars have also studied channels such as manufacturer direct sales channels, both online and offline channels (Liu et al., 2016; Li et al., 2017; Mondal et al., 2020; Wang et al., 2020; Wang et al., 2021). "Game theory" represents the game approach used, and the Stackelberg game is used in this paper.

2 Model assumptions

The research object of this article is a two-level supply chain composed of a manufacturer and a retailer. Manufacturers manufacture products at unit product cost c, and retailers purchase products from manufacturers at wholesale price w and sell them to consumers at retail price p. Manufacturers dominate the supply chain; retailers follow manufacturers in the Stackelberg game; the information between the two sides is wholly shared. The relevant parameter symbols are shown in Table 2.

In Table 2, a list of the symbols and variables used in the study is shown. Retail pricing and product greenness make up the two parts of market demand, according to Xu and Liu (2014). Based on this, the model introduces reference price effects $\lambda(p-r)$ and manufacturer risk aversion coefficients R (Xie et al., 2011). The profit functions of retailers and manufacturers were built under the two-level green supply chain. Similar to Wang et al. (2020), Ghosh and Shah (2015), and Shen (2021), the manufacturer and retailer play the Stackelberg game, where the manufacturer decides the wholesale price w and the product's degree of greenness θ. The retailer will then decide on the retail price. Retailers and manufacturers compete for maximum profitability. π represents profit, whereas subscript r, m, sc represents the retailer, manufacturer, and supply chain

system. U represents utility since the retailer has no risk-averse behavior, i.e., $U_r = \pi_r$. The following assumptions mention the additional Table 2 parameters, so we will not repeat them here.

For the purpose of modeling, the following assumptions are made in this paper.

1) Market demand d is a general linear function of the retail price p and product greenness θ (Xu and Liu, 2014; Yao et al., 2022). Market demand is

$$d = a - \beta p + k\theta - \lambda(p - r) \tag{1}$$

Where, a indicates the potential market demand, $a = \alpha + \varepsilon$, ε is a requirement random parameter that obeys a mean of zero and normal distribution with a variance of σ^2 (Tang, 2006; Yue and Liu, 2006). β is the elasticity of market demand d to the retail price p. k is the elasticity coefficient of market demand d on the greenness of the product θ. λ represents the elasticity coefficient of the difference between the consumer's retail price p and the reference price r of the product.

2) The manufacturer has a risk-averse behavior, and the retailer has no risk behavior, i.e., the retail utility function U_r is equal to its profit function π_r. A manufacturer's utility function U_m is an exponential function of its degree of risk aversion R, i.e.; $U_m = -e^{-R\pi_m}$; $R > 0$. The manufacturer's profit function π_m follows a normal distribution: the mean is $E(\pi_m)$, and the variance is $Var(\pi_m)$. The manufacturer's utility function is $U_m = E(\pi_m) - RVar(\pi_m)/2$ (Xie et al., 2011).
3) In order to produce green products, manufacturers need to invest a certain amount of money. It is a quadratic function between the manufacturers' green input costs $c(\theta)$ and the product's greenness θ, i.e., $c(\theta) = \eta\theta^2/2$. Where, η is the elasticity of the cost of green manufacturing inputs to product greenness.

As a result, manufacturers' and retailers' functions are

$$U_r = (p - w)(\alpha - \beta p + k\theta - \lambda(p - r)) \tag{2}$$

Where $p - w$ represents the difference between the retail price and the wholesale price, i.e., the retailer's revenue per unit of product. $\alpha - \beta p + k\theta - \lambda(p - r)$ denotes the market demand considering the product's greenness and the reference price effect, which is the same as Eq. 1.

$$U_m = (w - c)(\alpha - \beta p + k\theta - \lambda(p - r)) - \frac{1}{2}\eta\theta^2 - \frac{1}{2}R(w - c)^2\sigma^2 \tag{3}$$

Where $w - c$ represents the difference between the wholesale price and the cost of generation, i.e., the manufacturer's revenue per unit of product. $\alpha - \beta p + k\theta - \lambda(p - r)$ is the same as Equation 1 above, indicating market demand. Manufacturers need to invest in the development costs to generate green products $\eta\theta^2/2$. $R(w - c)^2\sigma^2/2$ indicates the loss of revenue due to manufacturer risk aversion.

3 Model analysis

For ease of analysis, superscript C denotes the equilibrium model under centralized decision-making, superscript D denotes the equilibrium model under decentralized decision-making, and superscript CS denotes the equilibrium model under cost-sharing contracts.

3.1 Centralized decision model

Under centralized decision-making, manufacturers and retailers are viewed as a whole, and make joint decisions to maximize the expected utility of the supply chain. The decision variables are wholesale price w, retail price p, and product greenness θ. Then the total supply chain profit function under the centralized decision model is

$$\pi_{sc} = (p - c)(\alpha - \beta p + k\theta - \lambda(p - r)) - \frac{1}{2}\eta\theta^2 - \frac{1}{2}R(w - c)^2\delta^2 \tag{4}$$

Proposition 1 Under the centralized decision model, there is a single best solution for the total profit function of the supply chain when $k^2 < 2\eta(\lambda + \beta)$. The optimal decision is specified as follows

$$w^C = c \tag{5}$$

$$\theta^C = \frac{k(c\lambda + c\beta - \alpha - r\lambda)}{k^2 - 2\lambda\eta - 2\beta\eta} \tag{6}$$

$$p^C = \frac{\eta(c\lambda + c\beta - \alpha - r\lambda)}{k^2 - 2\lambda\eta - 2\beta\eta} + c \tag{7}$$

Proof of Proposition 1

Under the centralized decision model, the Hessian matrix of the total supply chain profit function π_{sc} about the retail price p, the wholesale price w and the product greenness θ is

$$H^C = \begin{bmatrix} -2\lambda - 2\beta & 0 & k \\ 0 & -R\delta^2 & 0 \\ k & 0 & -\eta \end{bmatrix} \tag{8}$$

From the above Hesse matrix, the first-order principal subformula $-2\beta - 2\lambda < 0$, the second-order principal subformula $2R\delta^2(\lambda + \beta) > 0$, and the third-order principal subformula $R\delta^2(k^2 - (2\eta\lambda + 2\eta\beta)) < 0$ are obtained. Therefore, the Hesse matrix is a negative definite matrix. π_{sc} is a joint concave function concerning the retail price p, the wholesale price w, and the product greenness θ. So there is a single best solution for the total profit function of the supply chain π_{sc}. Under centralized decision-making, the optimal wholesale price w^C, the optimal retail price p^C and the optimal product greenness θ^C are obtained by letting the first-order partial derivatives of π_{sc} with respect to p, w and θ be equal to zero. Proposition 1 is proven.

Substituting Eqs. 5, 6, and Eq. 7 into Eq. 4, the total supply chain profit function can be obtained

$$\pi_{sc}^C = \frac{\eta(c\lambda + c\beta - \alpha - r\lambda)^2}{2(2\lambda\eta + 2\beta\eta - k^2)} \tag{9}$$

3.2 Decentralized decision model

Under the decentralized decision model, the manufacturer considers risk aversion, and the retailer is risk neutral. Furthermore, the retailer aims to maximize its own expected utility. Under the Stackelberg game, the manufacturer sets the wholesale price w and the greenness of the product θ first. Above this, retailers set the retail price p as followers of the manufacturer. The retailer's profit

function and the manufacturer's profit function under decentralized decision-making are given by Eqs 2, 3.

$$\pi_r = (p-w)(\alpha-\beta p+k\theta-\lambda(p-r)) \tag{10}$$

$$\pi_m = (w-c)(\alpha-\beta p+k\theta-\lambda(p-r))-\frac{1}{2}\eta\theta^2-\frac{1}{2}R(w-c)^2\delta^2 \tag{11}$$

Proposition 2 Under the decentralized decision model, there is a single best solution for the supply chain. The optimal decision is

$$w^D = \frac{2\eta(c\lambda+c\beta-\alpha-r\lambda)}{k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta}+c \tag{12}$$

$$\theta^D = \frac{k(c\lambda+c\beta-\alpha-r\lambda)}{k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta} \tag{13}$$

$$p^D = \frac{\eta(2R\delta^2+3\lambda+3\beta)(c\lambda+c\beta-\alpha-r\lambda)}{(\lambda+\beta)(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)}+c \tag{14}$$

Proof of Proposition 2

The inverse solution approach is used to resolve the decentralized decision model. First, the retailer's profit function π_r concerning the retail price p is discovered to be a first-order partial derivative. Let the value of this first-order condition be zero. And the optimal retail price response function is found as

$$p^D = \frac{k\theta+w(\lambda+\beta)+\alpha+r\lambda}{2(\lambda+\beta)} \tag{15}$$

Second, the manufacturer's profit function is produced by putting Eq. 15 into Eq. 11. π_m concerning the wholesale price w and the product greenness θ of the Hesse matrix is

$$H^D = \begin{bmatrix} -\lambda-\beta-R\delta^2 & \frac{1}{2}k \\ \frac{1}{2}k & -\eta \end{bmatrix} \tag{16}$$

From the above Hesse matrix, we have the first-order principal subformula $-\lambda-\beta-R\delta^2<0$, the second-order principal subformula $\eta(R\delta^2+\lambda+\beta)-k^2/4>0$. Therefore, the Hesse matrix is a negative definite matrix, π_m is a joint concave function concerning the wholesale price w and product's greenness θ, and π_m has a single best solution. Under decentralized decision-making, the optimal wholesale price w^D and the optimal product greenness θ^D are obtained by letting the first-order partial derivatives of π_m with respect to w and θ be equal to zero.

Finally, we obtain the optimal retail price p^D by substituting w^D and θ^D into Eq. 15. Proposition 2 is proven.

Putting Eqs 12, 13, 14 into Eqs 10, 11, the retailer profit function, the manufacturer profit function, and the total profit effect function can be obtained as

$$\pi_r^D = \frac{\eta^2(2R\delta^2+\lambda+\beta)^2(c\lambda+c\beta-\alpha-r\lambda)^2}{(\lambda+\beta)(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)^2} \tag{17}$$

$$\pi_m^D = \frac{\eta(c\lambda+c\beta-\alpha-r\lambda)^2}{-2(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)} \tag{18}$$

$$\pi_{sc}^D = \frac{\eta(c\lambda+c\beta-\alpha-r\lambda)^2 A}{2(\lambda+\beta)(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)^2} \tag{19}$$

Among them

$$A = 8R^2\delta^4\eta+12R\beta\delta^2\eta+12R\lambda\delta^2\eta+12\lambda\beta\eta+6\beta^2\eta+6\lambda^2\eta-\lambda k^2-\beta k^2$$

Proposition 3 Under the decentralized decision model, wholesale price w, product greenness θ, and retail price p are negatively related to the degree of risk aversion of the manufacturer R.

Proof of Proposition 3w^D, θ^D and p^D are obtained by taking the first-order derivatives of R, respectively

$$\frac{\partial w^D}{\partial R} = -\frac{8\delta^2\eta^2(\alpha+r\lambda-c\lambda-c\beta)}{(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)^2}<0 \tag{20}$$

$$\frac{\partial \theta^D}{\partial R} = -\frac{4k\delta^2\eta(\alpha+r\lambda-c\lambda-c\beta)}{(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)^2}<0 \tag{21}$$

$$\frac{\partial p^D}{\partial R} = -\frac{2\delta^2\eta(k^2+2\lambda\eta+2\beta\eta)(\alpha+r\lambda-c\lambda-c\beta)}{(\lambda+\beta)(k^2-4\eta R\delta^2-4\eta\lambda-4\eta\beta)^2}<0 \tag{22}$$

Proposition 3 is proven.

According to Proposition 3, as the level of manufacturer risk aversion reduces, optimal wholesale pricing, product greenness, and retail prices all rise. Manufacturers who are less risk averse, whose higher optimal wholesale prices correspond to reduced risk aversion, are encouraged to invest more in creating green products, which leads to a rise in the greenness of their products. Additionally, when manufacturers' risk aversion declines, retail prices rise in response. This is because retailers decide to raise retail prices to enhance profits, and *vice versa*, as optimal wholesale prices rise.

Proposition 4 Under the decentralized decision model, the retailer profit function is positively related to manufacturer risk aversion when $k^2>4R\delta^2\eta$, and the manufacturer profit function and total profit function are negatively related to manufacturer risk aversion R.

Proof of Proposition 4π_r^D, π_m^D and π_{sc}^D are obtained by taking the first-order derivatives of R, respectively

$$\frac{\pi_r^D}{R} = \frac{4\delta^2\eta^2(2\lambda\eta+2\beta\eta-k^2)(2R\delta^2+\lambda+\beta)(\alpha+r\lambda-c\lambda-c\beta)^2}{(\lambda+\beta)(4R\delta^2\eta+4\lambda\eta+4\beta\eta-k^2)^3}>0 \tag{23}$$

$$\frac{\pi_m^D}{R} = -\frac{2\delta^2\eta^2(\alpha+r\lambda-c\lambda-c\beta)^2}{(4R\delta^2\eta+4\lambda\eta+4\beta\eta-k^2)^2}<0 \tag{24}$$

$$\frac{\pi_{sc}^D}{R} = -\frac{2\delta^2\eta^2(\alpha+r\lambda-c\lambda-c\beta)^2(4R\delta^2k^2+(\lambda+\beta)(k^2-4R\delta^2\eta))}{(\lambda+\beta)(4R\delta^2\eta+4\lambda\eta+4\beta\eta-k^2)}<0 \tag{25}$$

Proposition 4 is proven.

According to Proposition 4, the manufacturer's profit function and total profit function decline as risk aversion rise, whereas the retailer's profit function rises as it does. The manufacturer's profit is also squeezed as its risk aversion level rises. In order to obtain more profit, the manufacturer takes measures to adjust the wholesale price and the level of product greenness so that it gains an advantageous position and minimizes the retailer's profit. Retailers and manufacturers aim to maximize their profits, which has a double marginal impact. The risk aversion of manufacturers reduces the benefits of supply chain members, aggravating the double marginal effect of the supply chain and reducing the total profit. Therefore, it is essential to create a suitable contract to coordinate the behavior of supply chain participants to benefit both manufacturers and retailers and increase the total profit of the supply chain.

4 Contract coordination

In order to produce green products, manufacturers must make significant financial investments. Nevertheless, when manufacturers have a risk-averse effect, they will inevitably choose to increase the wholesale price or reduce the greenness of their products in order to maximize their profits. This will impact on the market's demand for green products and lessen the advantages of supply chain participants, ultimately aggravating the double marginal utility. However, choosing a cost-sharing contract can lower the cost of manufacturers' investments. This is because consumers' preference for green products makes retailers willing to bear part of the cost of green products. The ratio of retailers bearing the input cost of green products is $g\,(0 < g < 1)$.

Under the cost-sharing contract model, the manufacturer and the retailer still follow the manufacturer-dominated Stackelberg game. The retailer's profit function and the manufacturer's profit function are

$$\pi_r = (p - w)(\alpha - \beta p + k\theta - \lambda(p - r)) - \frac{1}{2}\eta g\theta^2 \tag{26}$$

$$\pi_m = (w - c)(\alpha - \beta p + k\theta - \lambda(p - r)) - \frac{1}{2}\eta(1 - g)\theta^2 - \frac{1}{2}R(w - c)^2\delta^2 \tag{27}$$

The inverse solution method is applied to Eqs 26, 27. First, solve π_r for the first-order conditions of p to derive the optimal price function, which can be expressed as

$$p^{CS} = \frac{k\theta + w(\lambda + \beta) + \alpha + r\lambda}{2(\lambda + \beta)} \tag{28}$$

Next, the manufacturer's profit function is obtained by putting Eq. 28 into Eq. 27. Solving π_m^{CS} for the first order conditions on w and θ, we can get w^{CS} and θ^{CS}. Then p^{CS} is brought by putting w^{CS} and θ^{CS} into Eq. 28, which can be expressed as

$$w^{CS} = \frac{2(1 - g)\eta(c\lambda + c\beta - \alpha - r\lambda)}{k^2 - 4(1 - g)\eta(R\delta^2 + \lambda + \beta)} + c \tag{29}$$

$$\theta^{CS} = \frac{k(c\lambda + c\beta - \alpha - r\lambda)}{k^2 - 4(1 - g)\eta(R\delta^2 + \lambda + \beta)} \tag{30}$$

$$p^{CS} = \frac{(1 - g)\eta(2R\delta^2 + 3\lambda + 3\beta)(c\lambda + c\beta - \alpha - r\lambda)}{(\lambda + \beta)(k^2 - 4(1 - g)\eta(R\delta^2 + \lambda + \beta))} + c \tag{31}$$

The retailer's profit function can be given by putting Eqs 29, 30, 31 into Eq. 26, which can be expressed as

$$\pi_r^{CS} = \frac{\left(2(1 - g)^2\eta^2(2R\delta^2 + \lambda + \beta)^2 - (\lambda + \beta)g\eta k^2\right)(c\lambda + c\beta - \alpha - r\lambda)^2}{2(\lambda + \beta)(k^2 - 4(1 - g)\eta(R\delta^2 + \lambda + \beta))^2} \tag{32}$$

Again, the retailer splits a particular percentage g of the cost of manufacturing green products, but it determines the optimal g to maximize profit. Solving π_r^{CS} for the first-order condition on g, we get

$$g = \frac{16R^2\delta^4\eta + 12R\delta^2\lambda\eta + 12R\delta^2\beta\eta + \lambda k^2 + \beta k^2}{4\eta(4R^2\delta^4 + 5R\delta^2\lambda + 5R\delta^2\beta + 4\lambda\beta + 2\lambda^2 + 2\beta^2)} \tag{33}$$

Putting g into Eqs 29, 30, 31, we get

$$w^{CS} = \frac{(\lambda + \beta)(\alpha + r\lambda - c\lambda - c\beta)(8R\delta^2\eta + 8\lambda\eta + 8\beta\eta - k^2)}{2B} + c \tag{34}$$

$$\theta^{CS} = \frac{k(\alpha + r\lambda - c\lambda - c\beta)(4R^2\delta^2 + 5R\delta^2\lambda + 5R\delta^2\beta + 4\lambda\beta + 2\lambda^2 + 2\beta^2)}{B} \tag{35}$$

$$p^{CS} = \frac{(2R\delta^2 + 3\lambda + 3\beta)(\alpha + r\lambda - c\lambda - c\beta)(8R\delta^2\eta + 8\lambda\eta + 8\beta\eta - k^2)}{4B} + c \tag{36}$$

Among them

$$B = (16R\delta^2\eta - 3k^2)(\lambda + \beta)^2 + (8R^2\delta^4 - 6R\delta^2k^2 + 24\eta\lambda\beta)(\lambda + \beta) + 8\eta\lambda^3 + 8\eta\beta^3 - 4R^2\delta^4k^2$$

Finally, the manufacturer's optimal profit, the retailer's optimal profit, and the total supply chain profit can be given by putting Eqs 34, 35, 36 into π_r, π_m and π_{sc}, which can be expressed as

$$\pi_r^{CS} = \frac{(\alpha + r\lambda - c\lambda - c\beta)^2(32R^2\delta^4\eta + (\lambda + \beta)(32R\delta^2\eta + 8\eta\lambda + 8\eta\beta + k^2))}{16B} \tag{37}$$

$$\pi_m^{CS} = \frac{(\lambda + \beta)(\alpha + r\lambda - c\lambda - c\beta)^2(8R\delta^2\eta + 8\eta\lambda + 8\eta\beta - k^2)}{8B} \tag{38}$$

$$\pi_{sc}^{CS} = \frac{(\alpha + r\lambda - c\lambda - c\beta)^2(32R^2\delta^4\eta + (\lambda + \beta)(48R\delta^2\eta + 24\eta\lambda + 24\eta\beta - k^2))}{16B} \tag{39}$$

Proposition 5 When $4R\delta^2\eta > \eta(\lambda + \beta)$, manufacturer's profit, retailer's profit, and total profit are higher under the cost-sharing contract than decentralized decision-making.

Proof of Proposition 5

Compare the profits earned by the producer, the retailer, and the total profit.

$$\frac{\pi_r^{CS}}{\pi_r^D} = 1 + \frac{k^2(16R^2\delta^4\eta + 12R\delta^2\eta\lambda + 12R\delta^2\eta\beta + k^2\lambda + k^2\beta)^2}{16\eta^2(2R\delta^2 + \lambda + \beta)^2B} \tag{40}$$

$$\frac{\pi_m^{CS}}{\pi_m^D} = 1 + \frac{k^2(16R^2\delta^4\eta + 12R\delta^2\eta\lambda + 12R\delta^2\eta\beta + k^2\lambda + k^2\beta)}{4\eta B} \tag{41}$$

$$\frac{\pi_{sc}^{CS}}{\pi_{sc}^D} = \frac{(2\lambda + 2\beta)(4R\delta^2\eta - k^2 + 4\eta\lambda + 4\eta\beta)^2F}{4\eta(F - 3k^2\lambda - 3k^2\beta)B} \tag{42}$$

Among them

$$F = 32R^2\delta^4\eta + 48R\delta^2\eta\lambda + 48R\delta^2\eta\beta - k^2\lambda - k^2\beta + 24\lambda^2\eta + 48\lambda\beta\eta + 24\beta^2\eta$$

$\pi_r^{CS} > \pi_r^D$ and $\pi_m^{CS} > \pi_m^D$ can be obtained from Eqs 40, 41, which show that both the manufacturer's and retailer's profits are greater under the cost-sharing contract than under the decentralized decision.

From Eq. 42, we get

$$\frac{\pi_{sc}^{CS}}{\pi_{sc}^D} > \frac{(2\lambda + 2\beta)(4R\delta^2\eta - k^2 + 4\eta\lambda + 4\eta\beta)^2}{4\eta B} = 1 + \frac{k^2(8R^2\delta^4\eta + (\lambda + \beta)(4R\delta^2\eta + k^2 - 2\eta(\lambda + \beta)))}{2\eta B} \tag{43}$$

Further when Further when $k^2 > 4R\delta^2\eta > \eta(\lambda + \beta)$, $\pi_{sc}^{CS}/\pi_{sc}^D > 1$, so $\pi_{sc}^{CS} > \pi_{sc}^D$. i.e., the total profit of the supply chain under the

cost-sharing contract is more significant than its profit under the decentralized decision.

Proposition 5 is proven.

Proposition 5 illustrates that a cost-sharing contract can coordinate supply chain coordination in a green supply chain that considers manufacturer risk aversion and reference price effects. Unlike decentralized decision-making, where the manufacturer's profit, the retailer's profit, and the total profit are compared, the retailer bears a portion of the cost of the green product input, allowing for the optimal decision-making between the two parties and the supply chain. This shows that cost-sharing contracts boost supply chain members' profits and enhance their effectiveness.

5 Impact analysis

In this section, we analyze how manufacturer risk aversion affects supply chain profit, product greenness, and optimal pricing under the reference price effect and offer pertinent managerial revelations.

Proposition 6 The wholesale price under the cost-sharing contract and the wholesale price under the decentralized decision satisfy $w^{CS} > w^{D}$; the greenness of the product under the centralized decision, the greenness of the product under the decentralized decision, and the greenness of the product under the cost-sharing contract satisfy $\theta^{C} > \theta^{CS} > \theta^{D}$.

Proof of Proposition 6

By comparing w^{CS} and w^{D}, we obtain

$$\frac{w^{CS}}{w^{D}} = 1 + \frac{k^2(\alpha + r\lambda - c\lambda - c\beta)\left(16R^2\delta^2 + 12R\delta^2\eta\lambda + 12R\delta^2\eta\beta + k^2\lambda + k^2\beta\right)}{\left(8R\delta^2\eta c + 4r\eta\lambda + 4\alpha\eta + 2c\left(2\eta\lambda + 2\eta\beta - k^2\right)\right)B} \tag{44}$$

$w^{CS}/w^{D} > 1$ is given by Eq. 44, i.e., $w^{CS} > w^{D}$. By comparing θ^{CS} and θ^{D}, we obtain

$$\frac{\theta^{CS}}{\theta^{D}} = 1 + \frac{\left(R\delta^2 + \lambda + \beta\right)\left(16R^2\delta^4\eta + 12R\delta^2\eta\lambda + 12R\delta^2\eta\beta + k^2\lambda + k^2\beta\right)}{B} \tag{45}$$

$\theta^{CS}/\theta^{D} > 1$ is given by Eq. 45, i.e., $\theta^{CS} > \theta^{D}$.By comparing θ^{C} and θ^{CS}, we obtain

$$\frac{\theta^{C}}{\theta^{CS}} = 1 + \frac{(\lambda + \beta)\left(6R\delta^2\eta\lambda + 6R\delta^2\eta\beta - R\delta^2k^2 + (\lambda + \beta)\left(4\eta\lambda + 4\eta\beta - k^2\right)\right)}{\left(2\eta\lambda + 2\eta\beta - k^2\right)\left(4R^2\delta^2 + 5R\delta^2\lambda + 5R\delta^2\beta + 2\lambda^2 + 4\lambda\beta + 2\beta^2\right)} \tag{46}$$

$\theta^{C}/\theta^{CS} > 1$ is given by Eq. 46, i.e., $\theta^{C} > \theta^{CS}$.

In summary, $\theta^{C} > \theta^{CS} > \theta^{D}$. Proposition 6 is proven.

According to proposition 6, cost-sharing contracts have a better product greenness than decentralized decision-making, indicating that they can improve product greenness. However, product greenness is higher under centralized decision-making rather than cost-sharing agreements, indicating that cost-sharing agreements only partially coordinate the supply chain mechanism between upstream and downstream businesses. Cost-sharing contracts do not lower the product's wholesale price, resulting in higher wholesale prices than decentralized decision-making.

Proposition 7 The retail price under centralized decision, the retail price under decentralized decision, and the retail price under the cost-sharing contract satisfy $p^{C} > p^{CS} > p^{D}$.

Proof of Proposition 7

By comparing p^{CS} and p^{C}, we obtain

$$p^{CS} - p^{C} = \frac{(\alpha + r\lambda - c\lambda - c\beta)L}{\left(8\eta\lambda + 8\eta\beta - 4k^2\right)B} < 0 \tag{47}$$

Among them

$$L = 2R\delta^2k^2 + \left(16R\delta^2\eta^2 - 18k^2\eta\right)(\lambda + \beta)^2 + \left(3k^4 + 48\lambda\beta\eta^2 - 20Rk^2\delta^2\eta\right)(\lambda + \beta) + 16\eta^2\left(\lambda^3 + \beta^3\right)$$

From Eq. 47, we get $p^{C} > p^{CS}$.

Then by comparing p^{CS} and p^{D}, we obtain

$$\frac{p^{CS}}{p^{D}} = 1 + \frac{k^2\left(2R\delta^2 + 3\lambda + 3\beta\right)(\alpha + r\lambda - c\lambda - c\beta)\left(16R^2\delta^4\eta + \left(12R\delta^2\eta + k^2\right)(\lambda + \beta)\right)}{HB} \tag{48}$$

Among them

$$H = 8R\delta^2\eta(\alpha + r\lambda) + \left(8R\delta^2\eta c + 12r\eta\lambda + 12\alpha\eta - 4ck^2\right)(\lambda + \beta) + 4c\eta(\lambda + \beta)^2$$

From Eq. 48, we get $p^{CS}/p^{D} > 1$, i.e., $p^{CS} > p^{D}$.

In summary, $p^{C} > p^{CS} > p^{D}$. Proposition 7 is proven.

Proposition 7 illustrates that different decision models significantly impact retailers' decisions. Retail price is higher under centralized decision-making than under the cost-sharing contract and higher under decentralized decision-making. The relationship between retail prices and the degree of product greenness under various models continues to be consistent. This suggests that retail prices will increase as products become greener and product quality is assured.

Proposition 8 Total profit under centralized decision-making, total profit under decentralized decision-making, and total profit under the cost-sharing contract satisfy $\pi_{sc}^{C} > \pi_{sc}^{CS} > \pi_{sc}^{D}$.

Proof of Proposition 8 $\pi_{sc}^{CS} > \pi_{sc}^{D}$ follows from Proposition 5. In turn, by comparing π_{sc}^{C} and π_{sc}^{CS} , we obtain

$$\frac{\pi_{sc}^{C}}{\pi_{sc}^{CS}} = 1 + \frac{(\lambda + \beta)\left(\left(32R\delta^2\eta^2 + 2k^2\eta\right)(\lambda + \beta) + 16\eta^2(\lambda + \beta)^2 - k^4\right)}{\left(2\eta\lambda + 2\eta\beta - k^2\right)\left(32R^2\delta^4\eta + 48R\delta^2\eta\lambda + 48R\delta^2\eta\beta + 24\eta(\lambda + \beta)^2 - k^2(\lambda + \beta)\right)}$$

Because $k^2 < 2\eta(\lambda + \beta)$, therefore, $k^4 < 4\eta^2(\lambda + \beta)^2$, $k^2(\lambda + \beta) < 2\eta(\lambda + \beta)^2$. $\pi_{sc}^{C}/\pi_{sc}^{CS} > 1$,i.e., $\pi_{sc}^{C} > \pi_{sc}^{CS}$.

In summary, $\pi_{sc}^{C} > \pi_{sc}^{CS} > \pi_{sc}^{D}$. Proposition 8 is proven.

According to proposition 8, the cost-sharing contract can produce higher supply chain profits than decentralized decision-making, which can help the supply chain system coordinate and boost member earnings. However, supply chain profits under centralized decision-making are higher than supply chain profits under the cost-sharing contract, indicating that the cost-sharing contract can only partially coordinate supply chain systems. The cost-sharing contract improves the profitability of the supply chain participants and the product's greenness, even though it does not fully coordinate the system.

6 Simulation

We verified the relevant results using numerical simulations to explore further the effect of manufacturer risk aversion on green supply chain pricing and profitability under the reference price effect. It should be noted that, under a centralized decision-making model, the manufacturer and the retailer are in an ideal state when the optimal decision is that the manufacturer's wholesale price is the same as the

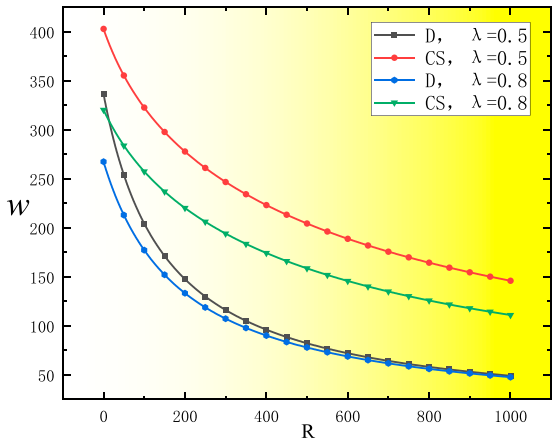

FIGURE 1
R impacts on wholesale prices.

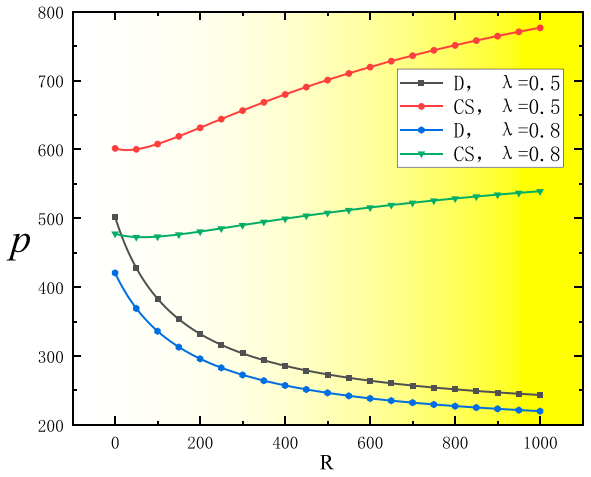

FIGURE 3
R impacts on retail price.

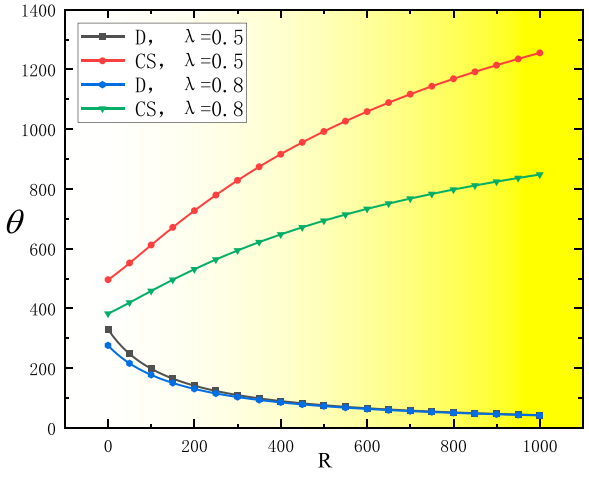

FIGURE 2
R impacts on the greenness of the product.

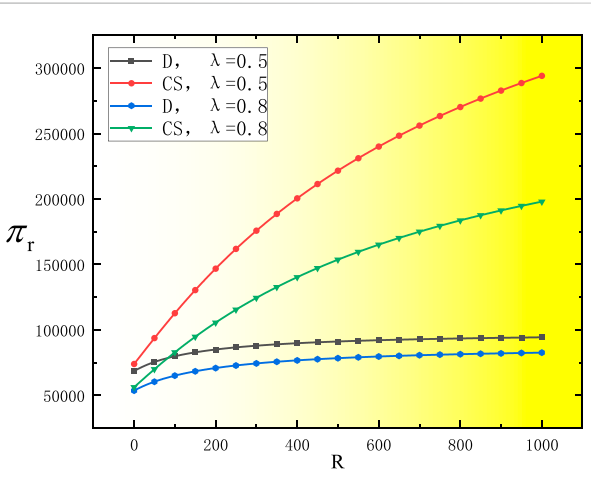

FIGURE 4
R impacts on retailer profit.

cost, i.e., $w = c$. The manufacturer's risk aversion factor has no impact on the wholesale price, retail pricing and supply chain profit. The numerical simulations compare only the best decisions made under a cost-sharing contract and decentralized decision-making. Parameters: market demand $\alpha = 1000$, retail price elasticity $\beta = 2$, unit product cost $c = 6$ (for manufacturers and retailers to be profitable, the cost must be lower than retail price p and reference price r), risk aversion variance $\delta = 0.1$ (The risk aversion variance can be found in Yue and Liu (2006)), reference price $r = 15$ (reference price is higher than cost), reference price elasticity $\lambda = 0.5$ *or* 0.8 (The range for the reference price effect λ is from 0 to 1. The model is the situation of no reference price effect when the reference price effect λ is 0.), product greenness elasticity $k = 2$, input cost elasticity $\eta = 1$.

The effect of manufacturer risk aversion on the optimal equilibrium strategy under the decentralized decision model and the cost-sharing contract model concerning the price effect is shown in Figures 1, 2, 3, 4, 5, 6.

As shown in Figure 1, under the decentralized decision process, wholesale prices converge with the manufacturer's degree of risk aversion when the degree of reference price effect is low. Under the cost-sharing contract, the wholesale price at $\lambda = 0.5$ is higher than that at $\lambda = 0.8$. Moreover, the wholesale price under decentralized decision-making and the cost-sharing contract decreases as the manufacturer's risk aversion rises. The wholesale price under the cost-sharing contract is consistently more significant than the wholesale price under decentralized decision-making, which remains consistent with the conclusion of Proposition 6. However, the wholesale price under the cost-sharing contract declines at a noticeably slower rate, and the gap between the two continues to widen. This is so that risk-averse manufacturers can keep their competitive edge by adjusting wholesale pricing. It is also clear from the decreasing gap between the two that the cost-sharing contract coordinates the supply chain system.

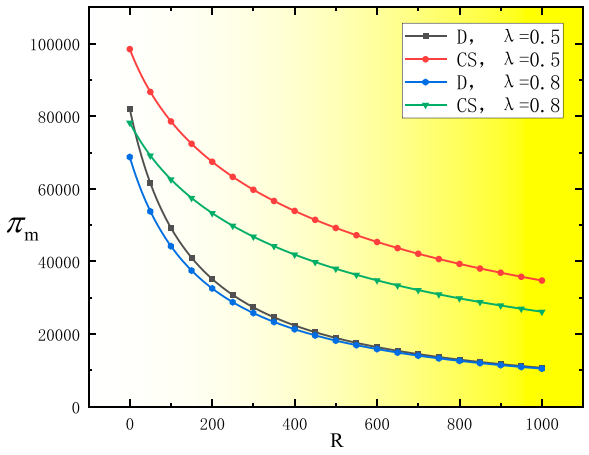

FIGURE 5
R impacts on manufacturer profit.

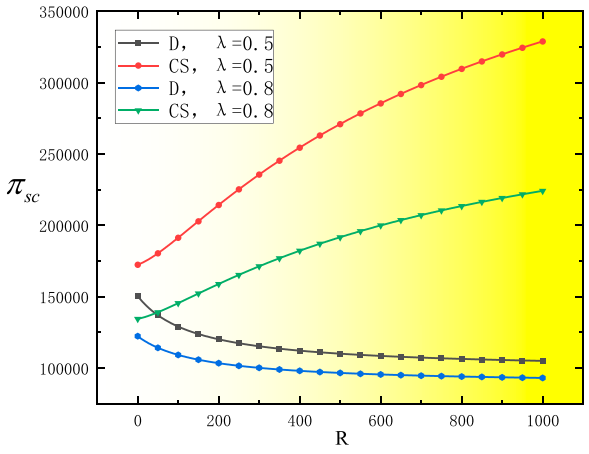

FIGURE 6
R impacts on total profit.

Figure 2, 3 show that under decentralized decision-making and cost-sharing contracts, product greenness and retail price at $\lambda = 0.5$ are both higher than product greenness and retail price at $\lambda = 0.8$. When the reference price effect is low, however, the level of greenness increases along with the level of manufacturer risk, which is consistent with the pattern of wholesale pricing seen in Figure 1. Under decentralized decision-making, the product's greenness and retail price decrease as the manufacturer's risk aversion increases, but under the cost-sharing contract, they are the opposite. It is also clear that the product's greenness and retail price are higher under the cost-sharing contract than in decentralized decision-making, which is consistent with the conclusion of Proposition 6 and Proposition 7. This shows that under the cost-sharing contract, retailers share a portion of the cost of green products, thereby increasing the greenness of the products. Additionally, wholesale and retail prices rise, increasing producers' and retailers' profits.

Figure 4 shows that under decentralized decision-making and cost-sharing contracts, retailer profit at $\lambda = 0.5$ is higher than retailer profit at $\lambda = 0.8$. As the manufacturer's risk aversion rises, the retailer's profit rises under decentralized decision-making and the cost-sharing contract. Additionally, retailers' profit under the cost-sharing contract is consistently higher than it is under decentralized decision-making, and the gap between the two is widening, which is consistent with the conclusion of Proposition 5. This demonstrates that a cost-sharing contract can coordinate the supply chain. The retailer partially bears the cost of the green product, but this does not affect its profitability. Promoting profit motivates retailers to take on product green costs, and the product's greenness has increased.

Figure 5 shows that under decentralized decision-making, the manufacturer's profit tends to be consistent with the degree of risk aversion when the reference price effect is low. Manufacturer profit at $\lambda = 0.5$ is higher than manufacturer profit at $\lambda = 0.8$ under the cost-sharing contract. Manufacturers' profit and wholesale pricing are consistent. The manufacturer's profit under the cost-sharing contract and the decentralized decision-making declines as the manufacturer's risk aversion rises. However, the manufacturer will profit more under the cost-sharing contract model than decentralized decision-making, which is consistent with the conclusion of Proposition 5. This means that manufacturers can bargain with retailers to bear a portion of the price of green products and select the cost-sharing contract. This can help them preserve their dominant position in the supply chain system and boost both sides' profits to create a win-win scenario.

Figure 6 shows that under decentralized decision-making and cost-sharing contracts, the overall supply chain profit at $\lambda = 0.5$ is higher than the total supply chain profit at time $\lambda = 0.8$. The total supply chain profit under the cost-sharing contract increases as the manufacturer's risk aversion rises. While the total supply chain profit under decentralized decision-making decreases, the difference between the two grows, which is consistent with the conclusion of Proposition 8. This is so because the cost-sharing contract coordinates the supply chain system, raising the product's greenness while also improving the profits of the manufacturer, retailer, and supply chain.

7 Discussion

In this paper, we study green supply chains' pricing and coordination decisions by considering that manufacturers have risk-averse preferences under the reference price effect. The optimal supply chain strategy under the centralized decision, decentralized decision, and cost-sharing contract is obtained using game theory. Further, discuss the coordination of the cost-sharing contract in the supply chain and analyze how manufacturer risk aversion affects supply chain member profits and optimal pricing.

Previous studies (Gan et al., 2004; Xie et al., 2011; Yang et al., 2018) have studied the pricing and coordination of risk-averse behavior in supply chains, but they have ignored the growing importance of green products among consumers and reality. Price factors also affect the purchase behavior of products. Based on the existing literature on the reference price effect (Malekian and Rasti-Barzoki, 2019; Ma and Hu, 2020) and risk aversion (Xiao and Yang, 2008; Zhang et al., 2022), this paper explored how supply chain participants adjust their optimal pricing strategies when manufacturer risk aversion occurs under the reference price effect. Therefore, this paper can offer product pricing and contract selection suggestions for green supply chain companies.

In the real-world business environment, market demand is uncertain, so companies make operational plans to make risk-averse decisions to minimize the loss of corporate revenue. However, the performance of the supply chain will be impacted by the decision-risk-averse maker's behavior, and the enterprise loss is irreparable. For instance, China.com reported on 17 July 2014, that the total stock of 42 domestically listed classes of clothing and textile companies, including Li Ning, Anta, 361°, Tebu, and Pique, was as high as 48.3 billion yuan based on the financial records for the first half of the year. Additionally, it is acceptable practice in the apparel sector to keep stock at 45% of the total cost. In order to reduce risk, businesses increase stock, but doing so comes at a stock cost. Businesses that want to maximize profits take into account their ability to accept risks and adopt a more cautious approach, giving up certain benefits in the process. Additionally, as the 5G era approaches, people are becoming more and more careful when buying products. Unlike traditional purchase behavior, consumers buy products to compare with reference price. Typically, these reference price is found on websites (such as Jingdong and Taobao.), in recommendations from friends, and on advertising posters. The reference pricing effect influences the supply chain participants' decision-making behavior. Complex settings impact how businesses make decisions, but there has not been any research on how manufacturer risk aversion affects supply chain decisions under the reference price effect. Studying manufacturers' risk-averse behavior under the reference price effect can help supply chain members develop better pricing strategies and thus improve total profit.

We provided a detailed investigation by establishing three decision models—centralized decision, decentralized decision, and cost-sharing contract—and calculating the best strategy under each model. We obtained the following findings. First, the reference price effect affects the supply chain system. The higher the reference price effect, the lower the product greenness, wholesale price, retail price, supply chain members' profit, and total profit. It is consistent with intuition. Because it makes intuitive sense that the higher the reference price effect, the more significant the gap between the retail price and the reference price, which can lower consumer desire and be harmful to both the greenness of the product and the profits of supply chain members (He et al., 2019). Second, with higher manufacturer risk aversion, decentralized decision-making decreases wholesale price, product greenness, retail price, manufacturer's profit, and overall profit, but a slight increase in retailer profit. Among a cost-sharing contract, product greenness, retail pricing, retailer profit, and overall supply chain profit rise dramatically, whereas wholesale price and manufacturer profit decrease as manufacturer risk aversion rise. According to Shengju (2020), a cost-sharing contract leads to higher greening, wholesale price, retail price, and manufacturer profit. Finally, it is found that the optimal decisions under a cost-sharing contract are better than those under decentralized decisions after introducing a cost-sharing contract to coordinate the green supply chain. According to Yang and Gong (2021), using a cost-sharing contract for Pareto improvement of green supply chains was found to positively impact the chains' performance and coordinate the chains effectively. This is congruent with the findings of Song et al. (2022), who found that a cost-sharing contract boosts the revenues of supply chain participants, and other scholars are consistent with this (Ghosh and Shah, 2015; Taleizadeh et al., 2018). It again demonstrates that a cost-sharing contract improves the environmental friendliness of products, the sustainability of supply chain members, and total profit.

The above finding makes it clear that, in any situation, the manufacturer's risk-averse behavior in the decentralization decision results in a decrease in the supply chain's efficiency. In other words, product greenness, wholesale price, manufacturer profit, and overall profit all decline. To avoid and reduce manufacturers' risk-averse behavior, the government and business-related departments must adopt policies and measures. For instance, the government has enacted measures to protect product prices and subsidize green products. Further, the coordination mechanism between upstream and downstream enterprises can be strengthened to change the cooperation mode of enterprises, improve the efficiency of the supply chain, and increase the members' benefits.

However, there are some limitations to this paper. It only considers the risk aversion of the manufacturer under the reference price effect, ignoring the risk preferences of the retailer and other behaviors. For the coordination of supply chain systems, only the cost-sharing contract is used, while additional coordination contracts may be included for comparative analysis. In addition, this paper consists of a second-order green supply chain system with one manufacturer and one retailer. Then the pricing and coordination research of a green supply chain system with numerous manufacturers and retailers can be considered.

8 Conclusion

Under the reference price effect, the pricing and coordination of a green supply chain with a risk-averse manufacturer are examined in this study. We explore the coordination of the cost-sharing contract on the supply chain and study the effects of manufacturer risk aversion on the pricing and profitability of the green supply chain. Through numerical simulations, we get the following findings.

1) Manufacturer profit, retailer profit, and total supply chain profit are all higher under the cost-sharing contract than under the decentralized decision. This shows that the cost-sharing contract can help the supply chain system work together, giving manufacturers, retailers, and the supply chain system the opportunity to all win. Because of this, companies can choose cost-sharing agreements to promote profits while making greener products.
2) In the cost-sharing contract, the total supply chain profit is less than it is under the centralized decision. As a result, it can be seen that the cost-sharing contract can only partially coordinate the supply chain system.
3) Product greenness increases with the manufacturer's risk aversion and retail price under cost-sharing contracts, during product greenness and retail price increase in the opposite direction under decentralized decision-making. This shows that the cost-sharing contract raises retail pricing, boosts product quality, and increases the product's greenness. A consistent relationship can be found between product greenness, retail pricing, and total supply chain profit. This implies that companies can promote green products more aggressively, raise customer acceptance, and educate consumers about green consumption to increase supply chain system profit.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

ZC: Conceptualization (lead); writing-original draft (lead); formal analysis (lead); writing-review and editing (equal); software (lead). LS: Conceptualization (supporting); writing-review and editing (equal). YW: formal analysis (supporting); writing-review and editing (equal).

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.

Publisher's note

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Environmental protection tax and total factor productivity—Evidence from Chinese listed companies

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By improving its total factor productivity, China may attain higher quality and more sustainable economic growth. As a key market-based incentive for environmental regulation, does environmental protection tax increase total factor productivity and provide a win-win situation for both economic and environmental performance? It is a debate-worthy topic. Based on data of Chinese listed companies, this paper uses the triple difference method to analyze China's environmental protection tax reform as a natural experiment. The results show that the environmental protection tax can significantly boost the firm's total factor productivity by encouraging technological innovation and enhancing resource allocation. Based on analysis of heterogeneity, it appears that state-owned enterprises, larger corporations, and regions with more strict environmental enforcement are more responsive to environmental protection tax policies. This report provides critical empirical evidence for upgrading China's tax framework to protect the environment.

KEYWORDS

environmental protection tax, total factor productivity, porter hypothesis, environmental regulation, the triple difference estimator

1 Introduction

Since the reform and opening up, China's economy has grown and developed rapidly, accomplishing incredible achievements. Due to the rising issues of climate change, environmental pollution, and resource shortages, China must urgently accelerate the transformation of its economic development mode, promote sustainable economic development, and build China into a country with a good environment (Liu et al., 2022). President Xi Jinping emphasized that we must plan for development from the perspective of harmony between humankind and nature. Early on in the history of environmental governance, the Chinese government primarily implemented command-and-control environmental laws and regulations and assumed complete responsibility for environmental protection (Karplus et al., 2021). In recent years, the Chinese government has paid significant attention to market-based environmental regulation in an attempt to strengthen the market's natural incentive function. Taxation is a crucial method of macroeconomic management and control, as well as a critical instrument for social and economic development. The environmental protection tax system transfers the external cost of environmental pollution into the internal cost of the direct polluter (Rugman and Verbeke, 1998; Chiroleu-Assouline and Fodha, 2014). It is crucial to promote the green transformation of traditional businesses and to coordinate the upgrade of industrial structures. With the growing attention on environmental protection concerns in western industrialized nations since the 1970s, a rather mature environmental tax system based on the "polluter pays" principle has been established. However, China's tax system for environmental protection is still in its infancy, as it was only officially established in 2018,

attracting worldwide attention. Scholars and policymakers are concerned with whether the implementation of the environmental protection tax system contributes to achieving a win-win economic and environmental performance and sustainable development as China's economy transitions from high-speed growth to a new stage of high-quality development.

Total factor productivity is the surplus remaining after deducting the growth of core factor input and its contribution to economic growth; it represents the level of production efficiency and the extent of technical advancement. With the transformation of China's economic growth pattern, the enhancement of total factor productivity has become a requirement for the formulation and implementation of policy. The Communist Party of China at the 20th convention makes it abundantly clear that we must focus our efforts on improving total factor productivity, and promoting the effective improvement of quality and reasonable growth of the economy. After China's economy enters a new stage of development, improving the total factor productivity is a critical concern that must be resolved without delay. Studies have explored the path of improving the total factor productivity of enterprises from government macro-control policies (Bartelsman et al., 2013; Alfaro and Chari, 2014), financial friction (Ziebarth, 2013; Midrigan and Xu, 2014; Lin et al., 2022), market information (Bennett et al., 2020), information and communication technology (Shao and Lin, 2016; Xie et al., 2020), and exchange rate fluctuations (Cao et al., 2022) and other aspects. Other studies have also explored the impact of environmental regulation on the total factor productivity of enterprises (Albrizio et al., 2017; Shen et al., 2019; Peng et al., 2021), however, most of them focus on command-and-control environmental policies and emission trading systems, and there is limited research on China's environmental protection tax. This paper utilizes the "natural experiment" of China's environmental protection tax to precisely identify the effect of environmental protection tax on the total factor productivity of enterprises, which has important theoretical and practical implications for evaluating the economic effects of green tax policies.

China's tax system for environmental protection dates back to the late 1970s and early 1980s. The Environmental Protection Law of the People's Republic of China (for Trial Implementation), promulgated in September 1979, for the first time introduced pollution charges, which were implemented on a trial basis in some locations. The State Council promulgated the Regulations on the Administration of the Collection and Use of Pollution Charge Fees in March 2003, which completely implements the pollution charge system and serves as a significant instrument for government environmental regulation. Although the pollution charge system can internalize the externalities of environmental pollution, problems such as low pollution charge standards, excessive administrative intervention, insufficient law enforcement, and a lack of standardization make it difficult to adapt to China's current practical environmental protection and economic development requirements. The Environmental Protection Tax Law of the People's Republic of China was adopted on 25 December 2016, and went into effect on 1 January 2018. This is the first tax law in China that expressly represents the "green tax system" and strives to protect the environment. It is essential for companies to establish internal pollution control and emission reduction restraining mechanisms and for China to develop an environment-friendly society. The reform of China's environmental protection tax has resulted in the transition from a pollution charge system to an environmental protection tax with the following characteristics: First, the tax burden is transferred. The Environmental Protection Tax Law is consistent with the pollution charge system in terms of objects, collection items, calculation methods, and standards to ensure a smooth and stable transition from the pollution charge system to the environmental protection tax system and to prevent a significant increase of cost in enterprises. Second, the legislative level has also been raised. The environmental protection tax system relies on state mandatory legislation to guarantee implementation, and the legal effect is stronger, which is conducive to enhancing the environmental protection consciousness of businesses as well as their responsibility for pollution control and emission reduction. The collection of sewage fees is an administrative supervisory behavior that is solely supported by administrative norms and lacks implementation and supervision. Third, the tax burden is flexible. According to the Environmental Protection Tax Law, minimum requirements are established for major pollutants, and local governments may increase the standard by up to 10 times the minimum criteria; hence, regions have the ability to choose the collection standard for significant pollutants. After the implementation of the Environmental Protection Tax Law in 2018, some regions have kept the original pollution fee collection standard, while others have chosen a higher collection requirement. This is similar to a "natural experiment" with obvious exogenous characteristics in the area of economics, offering a unique chance to evaluate the influence of China's environmental protection tax on the total factor productivity of firms.

Based on Chinese listed companies' data, this paper uses the implementation of China's environmental protection tax as a natural experiment and uses the triple difference method to examine the impact of environmental protection tax reform on the total factor productivity of enterprises by comparing before and after the implementation of the environmental protection tax, the regions with the increase of environmental protection tax rate and the regions with the unchanged environmental protection tax rate, and the polluting industries relative to clean industries. Furthermore, a number of heterogeneity and robustness tests are conducted based on the type of property rights, the size of the firm, and regional law enforcement. The total factor productivity of enterprises in polluting industries and in regions with increased environmental protection tax rates is much higher than in regions with unchanged environmental protection tax rates and in clean industries.

Compared to prior studies, the potential contributions of this work can be described as flows. First, the perspective of the study is innovative. Environmental protection tax is the most prominent symbol of China's building of a green tax system, and it is an environmental economic policy instrument that may have a significant influence on the behavior of micro-enterprises. Studies on China's environmental protection tax concentrate primarily on enterprise performance (Jin et al., 2020), innovation (Liu and Xiao, 2022), and environmental protection investment (Tian et al., 2022), whereas there are few studies that examine corporate production efficiency and technical progress. This paper evaluates the policy effect of environmental protection tax from the perspective of enterprise total factor productivity, which is an important contribution to the research literature on the effect of China's environmental protection "fee-to-tax" policy, and deepens the understanding of the impact of market-based economic incentive

environmental regulation on enterprise total factor productivity, and serves as an essential reference for the promotion of environmental protection. Secondly, the research methodology is scientific. This paper uses the quasi-natural experiment of China's environmental protection tax system and the triple difference method, which not only avoids the endogeneity problems caused by only relying on environmental regulations measurement indicators such as environmental pollution expenditures, sewage charges, pollution emission reductions in the past (Cai et al., 2016), but also eliminates the interference of other policies during the pilot period and the interference of time-varying regional characteristics (Olden and Møen, 2022). It improves the accuracy with which policy impacts are evaluated. Thirdly, this paper provides micro evidence that environmental protection taxes influence the total factor productivity of businesses. This paper analyzes the influence mechanism of environmental protection tax on enterprises' total factor productivity from the perspectives of capital allocation efficiency and technological innovation and investigates the strategic behavior of enterprises to enhance production efficiency under the pressure of environmental protection tax with stricter enforcement. It provides empirical data to demonstrate how government departments increase the total factor productivity of enterprises by utilizing market-based economic and environmental policy instruments to force and stimulate corporate subject responsibility awareness. In addition, it provides excellent references for the future improvement and optimization of the environmental protection tax system. It has significant practical implications for constructing a green development system and fostering high-quality economic growth.

The other sections of this paper are organized as follows. Section 2 presents the literature review and research hypothesis. Section 3 explains the research design and data. Section 4 presents the results of the empirical study. Section 5 presents a further discussion, including mechanism analysis and heterogeneity analysis. Section 6 concludes the study as well as gives some policy recommendations.

2 Literature review and research hypothesis

2.1 Literature review

The influence of environmental regulation on the total factor productivity of enterprises has become a major area of research in economics, however, the conclusions are inconsistent. From the perspective of neoclassical economics, the regulatory pressure brought by environmental policies will increase the cost of pollution and tax burdens on enterprises, resulting in the crowding out of resources from "production" purposes toward "pollution control" purposes, thereby impeding the development and negatively affecting the production efficiency of enterprises (Jorgenson and Wilcoxen, 1990; Shadbegian and Gray, 2005; Lanoie et al., 2011; Tombe and Winter 2015). He et al. (2020) discovered that China's water quality monitoring system immediate upstream polluters risk a total factor productivity decrease of more than 24%. Cai and Ye (2020) found that China's new environmental protection law inhibits enterprises' TFP with the impacts lasting for 2 years. Porter as well as other economists are opposed to this. The Porter Hypothesis (Porter, 1991; Porter and Van der Linde, 1995) asserted that strict and appropriate environmental regulation, particularly market-based tools, can enable businesses to positively adapt through innovation incentives, efficiency improvement, and internal redistribution, resulting in increased productivity. There are additional researches that support this conclusion (Ai et al., 2020). Both market-based and non-market-based policies promote productivity development, while green taxes have the greatest influence (De Santis et al., 2021). Peng et al. (2021) argued that China's SO2 Emissions Trading Pilot provides favorable benefits to productivity. According to additional research, the influence of environmental legislation on the total factor productivity of businesses is ambiguous. Albrizio et al. (2017) discovered that environmental regulation had a short-term influence on productivity development at the industry level in the most technologically advanced nations, but had no effect on the typical company. Zhao et al. (2018) discovered a substantial inverted U-shaped correlation between environmental regulatory intensity and the total factor production, and Qiu et al. (2021) also discovered that the similar link between environmental rules and green total factor production.

In conclusion, the existing research on the impact of environmental regulation on total factor productivity has yielded a number of significant findings. However, no consistent finding has been established due to differences in environmental regulations among nations, samples, and study techniques. Even less research has been conducted on the impact of a market-based economic incentive environmental policy instrument at the micro level. In view of this, and based on the 2018 implementation of China's environmental protection tax, this study investigates the impact and mechanism of environmental protection tax on the total factor productivity of firms, therefore extending previous research.

2.2 Research hypothesis

As an important market-based economic incentive environmental regulatory instrument, the environmental protection tax solves the market failure problem by internalizing the environmental externality costs of enterprises. Although the environmental protection tax raises the financial burden on businesses, it may distort the allocation of components, resulting in a reduction in earnings, preventing businesses from making optimal production decisions, and thereby decreasing their production efficiency and competitiveness (Cainelli et al., 2015; Tombe and Winter 2015). However, this viewpoint is "static." It holds that in implementing environmental protection policy, enterprises will just passively accept environmental protection tax costs, disregarding the environmental protection tax's compelled effect on pollution control and technological upgrading, as well as its positive impacts. From the perspective of long-term dynamic development, faced with the pressure of rising environmental compliance costs, enterprises can flexibly choose technological innovation and optimize resource allocation to improve production efficiency, thus further reducing production costs, and ultimately mitigating or offsetting the negative impact of environmental protection tax, thereby achieving environmental and economic dividends (Rubashkina et al., 2015). As the different features of technological innovation and resource allocation, the effect of environmental tax policy may be classified into long-term and short-term effects, but the overall effect will be positive. Therefore, this paper proposes the core hypothesis 1 to be tested:

Hypothesis 1: The implementation of an environmental protection tax can improve the total factor productivity of enterprises.

Innovation is a high-risk, high-investment, and high-turnover activity for enterprises (Bansal and Hunter, 2003), which is difficult to initiate. Technology's public good characteristics are determined by its non-competitive nature, and thus lacks innovation drive and requires external incentives. Before introducing the environmental protection tax, the pollution charge system was also a market-based economic incentive for environmental regulation. However, it is not incorporated into the tax law management system. Due to the absence of enforcement and insufficient supervision, the effect of the implementation is poor. Currently, businesses seeking maximum profit are often more willing to pay environmental punishment costs than to invest in greater R&D and innovation expenditures, and their desire to engage in technological innovation activities is low. After the implementation of the environmental protection tax policy, environmental regulation becomes more stringent and the corporate tax burden increases. To maximize economic benefits, businesses will be more motivated to use technological innovation initiatives that minimize pollution and manufacturing costs (Hattori, 2017; Wang et al., 2021). Moreover, the implementation of the environmental protection tax system demonstrates the Chinese government's determination and policy development direction to protect the environment, therefore increasing public awareness of environmental protection, and this social monitoring will enhance corporate innovation (Liu and Xiao, 2022). Furthermore, corporate technology innovation may be classified as invention technology innovation and non-inventive technology innovation. The latter includes utility patent and design innovation. Due to the high development difficulty and high resource investment associated with invention technology innovation, companies are more likely to embrace non-inventive technology innovations with low technical requirements and less development difficulty, also known as strategic innovation. Therefore, this paper suggests the core hypothesis 2 to be tested:

Hypothesis 2: The environmental protection tax system encourages enterprises to increase their total factor productivity through technological innovation; however, the environmental protection tax has a more significant incentive effect on utility model and design technology innovation than on invention technology innovation.

Besides the development of technology, the increase in production efficiency is also evident in the improvement of resource allocation efficiency within companies. The regulatory pressure and cost pressure imposed by the environmental protection tax policy encourage companies to decrease resource input in departments with higher pollution and lower production efficiency, while increasing investment in departments with larger cleanliness and higher production efficiency, thereby reducing the environmental protection tax burden. By optimizing the allocation of production factors, enterprises may help low-polluting and high-efficiency sectors gain additional production resources, as well as increase factor utilization and production efficiency (Wang et al., 2016; Ren et al., 2019; Yu et al., 2019). Therefore, this paper proposes the core hypothesis 3 to be tested:

Hypothesis 3: The environmental protection tax system encourages enterprises to improve total factor productivity by optimizing resource allocation.

3 Research design and data

3.1 Research design

To obtain credible causal inference, this article investigates the influence of environmental protection tax reform on the total factor productivity of businesses primarily through the triple difference method. Specifically, first of all, this paper compares the impact before and after the environmental protection tax reform using the time dimension as the primary distinction. Secondly, this paper takes the regional dimension as the second difference to compare the effect of the difference in environmental regulation intensity between regions with higher environmental tax rates and regions with unchanged environmental tax rates. This is because regions with higher taxation standards for taxable pollutants have greater environmental pressures and impacts on enterprises in these regions than regions with unchanged taxation standards for taxable pollutants. Thirdly, because environmental regulations primarily affect industries that directly release air pollutants, water pollutants, solid waste, and other taxable pollutants into the environment, clean industries that emit less or virtually no taxable pollutants will be affected very little (Hering and Poncet, 2014), the pollution level of the industry is used as the third distinction. By comparing the changes in total factor productivity of enterprises in polluting industries and clean industries before and after the environmental protection tax reform, in areas where the environmental protection tax rate was increased and unchanged, and by excluding as much as possible the influences of factors that do not change over time, are difficult to observe, and are outside the reform policy, this paper establishes the following benchmark model (Deschenes et al., 2017; Liu and Xiao, 2022):

$$y_{irjt} = \beta Post_t * Reform_r * Polluted_j + \rho X_{it} + \gamma_{rt} + \delta_{rj} + \mu_{jt} + \theta_i + \varphi_t + \varepsilon_{irjt}$$

In the model, i, j, r and t respectively represent the enterprise, industry, region, and time. The explained variable y_{irjt} is the total factor productivity of the enterprise. $Post_t$ is a dummy variable for the implementation time of environmental protection tax. $Post_t$ is 0 before 2018 and 1 after 2018. $Reform_r$ is the region dummy variable for the adjustment of the pollutants tax standard. $Reform_r$ is one for the regions where the tax standard of taxable pollutants is increased are the experimental group regions and 0 for the regions where the tax standard of taxable pollutants remains unchanged. $Polluted_j$ is the industry pollution characteristic variable. $Polluted_j$ is one if the industry is heavily polluting and 0 otherwise. $Post_t * Reform_r * Polluted_j$ is the core explanatory variable of the model, and its coefficient estimate is a triple difference estimator. It examines the difference of listed companies' total factor productivity before and after the implementation of the environmental protection tax, between regions where the environmental protection tax rate increases and regions where it remains unchanged, and between polluting industries and clean industries. At the same time, according to the existing research model, we control the variables X_{it} that may affect the total factor productivity of enterprises, including debt level, profitability, liquidity and governance structure. Finally, the model introduces three sets of two-dimensional fixed effects γ_{rt}, δ_{rj}, μ_{jt}, which are used to control region-time fixed effects, industry-time fixed effects, and region-industry fixed effects, to further consolidate the reliability of causal

TABLE 1 Summary statistics of main variables.

Variable	(1)	(2)	(3)	(4)	(5)
	N	Mean	Sd	Min	Max
TFP	21,913	10.92	0.627	9.461	12.85
Post*Reform*Polluted	21,913	0.0780	0.268	0	1
Lev	21,913	40.96	20.24	0.836	99.76
Roe	21,913	−0.0050	2.146	−186.6	64.06
Liquidity	21,913	57.95	19.83	1.856	99.96
LargestHolderRate	21,913	33.38	14.70	0.290	89.99

identification in policy evaluation. θ_i is the firm-fixed effect and controls the influence of factors that do not change with time at the firm level on the total factor productivity, and φ_t is the time-fixed effect and controls the influence of factors that do not change with the firm at the time level on the total factor productivity. ε_{irjt} is a random disturbance term. This paper performs clustering standard errors at the provincial level.

3.2 Data

3.2.1 Data sources

This sample comprises Chinese A-share companies listed on the Shanghai and Shenzhen stock exchanges between 2015 and 2021. Excluded from the sample are financial firms, companies with continuous losses, companies with asset-liability ratios larger than 1, and companies with significant missing values. Financial data comes from the Wind and CSMAR databases. The basic patent data comes from the State Intellectual Property Office of China. To reduce the impact of outliers on the estimated findings, all continuous variables are truncated at the 1% and 99% levels.

3.2.2 Variables and descriptive statistics

The explained variable in this paper is the total factor productivity of listed companies. Currently, semi-parametric approaches, such as the Olley-Pakes (OP) method, the Levinsohn-Petrin (LP) method, and the Ackerberg-Caves-Frazer (ACF) method, are used to estimate total factor productivity at the micro-enterprise level. The OP method uses the investment as the proxy variable, whereas the LP method utilizes intermediate inputs. Due to the lack of investment data for some companies, this article employs the LP approach to calculate the total factor productivity of the companies as the explained variable in order to minimize sample size loss. This paper uses the total factor productivity calculated by the ACF method as a substitute explained variable to ensure the robustness of the benchmark regression results, as the ACF method can reduce the interference of endogenous problems in the production function on measurement results to some extent.

To provide objective estimates of policy impacts, this article controls variables that may influence enterprises' total factor productivity over time, such as debt levels, profitability, liquidity, and corporate governance (Ren et al., 2019). First of all, under the premise of an acceptable cost of debt, modest debt will enable businesses to raise funds, compensate for the lack of long-term development funds, and influence company choices and production efficiency. This paper uses the asset-liability ratio (Lev) to measure the debt levels of enterprises. Secondly, the more profitable an enterprise is, the more money it can generate and the more efficient it can be. This paper measures profitability based on return on equity (Roe). Furthermore, liquidity and governance structure are significant elements that influence the production and management efficiency of companies. This paper utilizes the ratio of current assets to total assets and the ownership ratio of the largest shareholder. The variables' descriptive statistics are displayed in Table 1. The minimum total factor productivity of enterprises is 9.461 and the maximum is 12.85, demonstrating that there are significant variations in production efficiency among enterprises.

4 Empirical analysis

4.1 Baseline regression

Based on the benchmark model, this paper controls various combinations of the time-fixed effect, region-fixed effect, industry-fixed effect and control variables in columns (1) to (3), as well as the individual fixed effect in column (4). The regression results of columns (1)–(3) in Table 2 reveal that the coefficients of the core explanatory variables $Post_t{*}Reform_r{*}Polluted_j$ are mostly positive and significant

TABLE 2 The impact of environmental protection tax policy on total factor productivity.

Variables	(1)	(2)	(3)	(4)
	TFP	TFP	TFP	TFP
Post*Reform*Polluted	0.156***	0.138***	0.150***	0.053***
	(3.42)	(3.21)	(3.44)	(3.28)
Lev	0.013***	0.013***	0.013***	0.003***
	(34.67)	(33.55)	(35.81)	(7.94)
Roe	0.017***	0.017***	0.017***	0.005***
	(3.13)	(3.11)	(3.12)	(2.79)
Liquidity	0.003***	0.003***	0.003***	0.006***
	(4.87)	(5.01)	(4.85)	(11.06)
LargestHolderRate	0.006***	0.006***	0.006***	0.001
	(7.33)	(7.47)	(7.51)	(0.94)
Constant	9.927***	9.977***	9.944***	2.066
	(189.10)	(190.61)	(187.50)	(0.86)
Observations	21,913	21,913	21,913	21,913
R-squared	0.221	0.222	0.222	0.221
Year FE	YES	YES	YES	YES
Province*Year FE	YES	YES		YES
Industry*Year FE	YES		YES	YES
Industry* Province FE		YES	YES	YES
Id FE				YES

Robust t-statistics in parentheses,***$p < .01$, **$p < .05$, *$p < 0.1$.

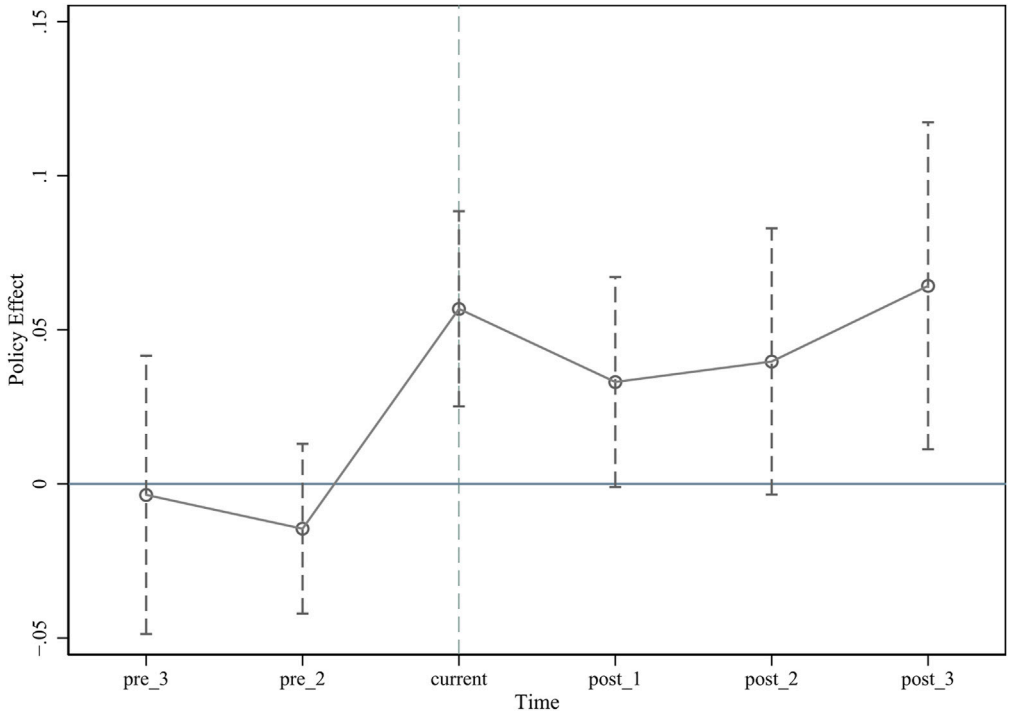

FIGURE 1
Parallel trend test.

at the 1% level. After adding the firm's individual fixed effect, the regression results in column (4) show that the coefficients of the core explanatory variables are very robust and are positively significant at the 1% level. This indicates that the environmental tax reform has a significant incentive effect on the total factor productivity of polluting enterprises in the regions where the taxable pollutant levy standards are raised. The regression results are robust to a certain extent, and Hypothesis one is verified, and this result is consistent with the "Porter Hypothesis".

4.2 Robustness tests

4.2.1 Parallel trend test

A parallel trend in the total factor productivity of enterprises in the treatment group and the control group prior to the adoption of the policy is required for an appropriate evaluation of policy impacts (Angrist and Pischke, 2009). In other words, when the experimental group is not exposed to policy shocks, the dependent variable should display the same temporal trend as the control group. In this paper, the event study method (Jacobson et al., 1993) is utilized to develop the following regression equation.

$$y_{irjt} = \sum_{k=-3}^{3} \beta_t Reform_r * u_k * Polluted_j + \rho X_{it} + \gamma_{rt} + \delta_{rj} + \mu_{jt} + \theta_i + \varphi_t + \varepsilon_{irjt}$$

u_k is a time dummy variable, and β_t represents the difference between the experimental group and the control group before and after the implementation of the policy. This paper selects the previous period of the implementation of the environmental protection tax policy (2017) as the base period, and the subscript k represents the number of periods that are different from the base period. Figure 1 demonstrates that, prior to the environmental protection tax reform, the difference between the experimental group and the control group is not statistically significant, i.e., there is no systematic difference between the total factor productivity of enterprises in the experimental group and the control group, and the model passed the parallel trend test. After the environmental protection tax reform, the polluting enterprises in the experimental group exhibit an upward trend in total factor productivity, with the biggest impact occurring during the present period and the third period of policy implementation. When the policy is implemented, enterprises will adjust their inputs and outputs such that production factors are weighted toward low-pollution and low-energy-consuming sectors, therefore lowering pollution at the source and enhancing production efficiency. Due to the long technology research and development cycle, there is a certain lag for enterprises to increase total factor productivity through technological innovation, therefore the effect is also greater in the third phase. This result is a little different from previous studies. Ren et al. (2019) found that there is a lagged effect of the emission trading system on total factor productivity for 2 years and they did not find the impact during the present period. This is possible because of the weak enforcement of the emission trading system, and companies lack the motivation to rearrange resources.

4.2.2 Using alternative variable measures

Due to the LP method used to estimate the total factor productivity of the company, there may be certain specific errors. This paper utilizes the ACF approach to recalculate the enterprise's total factor

TABLE 3 Robustness test.

VARIABLES	(1)	(2)	(3)	(4)
	TFP_ACF	TFP	TFP	TFP
Post*Reform*Polluted	0.046**	0.051***	0.070***	0.041**
	(2.36)	(3.18)	(3.45)	(2.71)
Lev	0.001	0.004***	0.002***	0.003***
	(1.35)	(7.88)	(5.03)	(5.65)
Roe	0.005**	0.067**	0.006*	0.006**
	(2.27)	(2.20)	(2.02)	(2.29)
Liquidity	0.011***	0.006***	0.006***	0.005***
	(17.01)	(11.88)	(10.73)	(8.87)
LargestHolderRate	−0.001	0.001	0.000	0.002
	(−1.00)	(0.60)	(0.13)	(1.54)
Constant	0.027	2.136	4.521	1.158
	(0.01)	(0.88)	(1.21)	(0.41)
Observations	21,913	21,839	13,604	13,590
R-squared	0.190	0.238	0.202	0.231
Number of Stkcd	4,388	4,378	2,692	2,701
Year FE	YES	YES	YES	YES
Pid*Year FE	YES	YES	YES	YES
Industry*Year FE	YES	YES	YES	YES
Industry*Pid FE	YES	YES	YES	YES

Robust t-statistics in parentheses,***$p < .01$, **$p < .05$, *$p < 0.1$.

productivity as the explained variable for robustness testing. Column (1) in Table 3 demonstrates that the environmental protection tax policy may greatly improve the total factor productivity of the enterprise, regardless of the method used to estimate it for regression, confirming the reliability of the baseline regression.

4.2.3 Propensity score matching

To reduce the disparities in individual characteristics between the treatment group and the control group, this research employs the propensity score matching approach to locate the most appropriate matching samples for the treatment group within the control group. This paper employs the year-by-year kernel matching approach (Heyman et al., 2007) and re-estimates using the matched data. The outcomes are displayed in column (2) of Table 3. The core explanatory factors are still significant. The environmental protection tax can greatly increase the total factor productivity of the company, and the reliability of the benchmark regression results has strengthened.

4.2.4 Falsification tests

In order to further strengthen the robustness of the conclusion, this paper excludes the influence of other policies that might affect the total factor productivity of firms and interfere with the results. In 2007, the Chinese government formally introduced the pilot project for paying for the use and trading of SO2 emission rights, and 11 pilot provinces, including Jiangsu, Tianjin, Shanxi, Chongqing, Hubei, Shaanxi, Inner Mongolia, Hunan, and Henan, were subsequently authorized. In 2011, China's National Development and Reform Commission issued the Notice on Conducting Pilot Programs for Carbon Emissions Trading, mandating that carbon emissions trading pilot projects be implemented in seven provinces and cities, including Beijing, Shanghai, Hubei, Chongqing, Guangdong, Tianjin, and Shenzhen. As environmental regulations, these two policies might have an effect on the total factor productivity of enterprises. Therefore, this research re-estimates the outcomes as presented in columns (3) and (4) of Table 3 by removing the data for these provinces from the sample, respectively. The continued significance of the results supports the validity of the paper's conclusions.

5 Further discussion

5.1 Mechanism analysis

The preceding research findings indicate that implementing an environmental protection tax policy can increase the total factor productivity of the company. Then, how does the tax on environmental protection impact the total factor productivity of enterprises? This paper adopts two methods of technological innovation and resource allocation to test the transmission mechanism, based on the preceding theoretical analysis.

5.1.1 Technological innovation

In order to examine whether the environmental protection tax improves the total factor productivity of enterprises through technological innovation, this paper uses patent authorization as a proxy variable for technological innovation in enterprises for empirical research (Ren et al., 2019). Indicating an enterprise's ability to innovate independently, a patent is an indication of the firm's investment in scientific research. This paper also conducts regressions on invention patents and non-invention patents (utility model patents and design patents) in order to evaluate specific types of technological innovation. Table 4 shows the findings in columns (1) and (2). It can be seen that the adoption of the environmental protection tax policy has a greater incentive effect on utility model and design innovation technology, indicating that the transition from the pollution charge fee system to the environmental tax system encourages polluters to boost their efforts in technological innovation. Nevertheless, considering the high difficulty of innovation and the long investment period of the invention of technology, the implementation of a pollution charge fee to tax has a greater impact on encouraging technological innovation in utility models and designs. Hypothesis two is confirmed.

5.1.2 Resource allocation

This research utilizes capital allocation efficiency as a proxy variable to evaluate the efficacy of enterprise resource allocation in order to determine whether the environmental protection tax can increase the total factor productivity of firms by improving the efficiency of resource allocation (Ren et al., 2019). Capital allocation efficiency = (cash paid for purchase and construction of fixed assets, intangible assets, and other long-term assets minus cash recovered through sale of fixed assets, intangible assets, and other

TABLE 4 Mechanism analysis.

VARIABLES	(1)	(2)	(3)
	Invpatent	NonInvpatent	Capital Allocation
Post*Reform*Polluted	0.016	0.092*	0.003*
	(0.41)	(1.90)	(1.83)
Lev	0.001*	0.004***	0.000
	(1.88)	(4.15)	(1.00)
Roe	0.002	0.001	−0.000
	(1.60)	(0.42)	(−1.21)
Liquidity	−0.001	−0.003***	−0.001***
	(−1.55)	(−3.90)	(−11.36)
LargestHolderRate	0.004**	0.008***	0.000***
	(2.14)	(4.11)	(3.90)
Constant	−7.641**	−24.697***	0.434***
	(−2.25)	(−5.51)	(2.88)
Observations	22,360	22,360	22,360
R-squared	0.042	0.177	0.044
Number of Stkcd	4,406	4,406	4,406
Year FE	YES	YES	YES
Pid*Year FE	YES	YES	YES
Industry*Year FE	YES	YES	YES
Industry*Pid FE	YES	YES	YES

Robust t-statistics in parentheses,***$p < .01$, **$p < .05$, *$p < 0.1$.

long-term assets)/total assets at the end of the period. The outcomes are displayed in column (3) of Table 4. The core explanatory variable's regression coefficient is significantly positive, suggesting that environmental protection tax policy can increase total factor productivity by optimizing the allocation of enterprise factors and enhancing resource consumption efficiency.

5.2 Heterogeneity analysis

Despite the fact that the environmental protection tax policy can increase the total factor productivity of enterprises, the promotion effect of environmental protection tax on the total factor productivity of enterprises may vary depending on regional characteristics and enterprise attributes. This research examines the variety of the influence of the environmental protection tax system on the total factor productivity of enterprises based on their internal and external features. The internal features of companies include corporate ownership and enterprise scale, whereas the external characteristics are mostly evaluated based on environmental law enforcement effectiveness. This will help the government in adapting policy implementation methods to the circumstances and in maximizing the policy impact of the environmental protection tax system.

5.2.1 Heterogeneity in ownership

In this study, the total sample is separated into state-owned and non-state-owned enterprises. The regression results for the two subsamples are shown in Table 5 columns (1) and (2). Overall, the treatment effect is robust in both subsamples. However, the estimated coefficient is smaller for non-state-owned enterprises than for state-owned enterprises. This suggests that state-owned enterprises under the environmental protection tax system are less likely to improve total factor productivity than state-owned enterprises. State-owned companies in China have generally consistent funding sources and certain resource advantages. They are able to invest adequate people, material, and financial resources in technological research and development, and have a high possibility of technological innovation success. Moreover, state-owned enterprises are subject to tougher government and public supervision, have a higher sense of social responsibility, and are more driven to adjust resource allocation within the enterprise, hence enhancing the utilization efficiency of production factors. Research and development capabilities of non-state-owned companies may be constrained by financial limitations. Additionally, the comparatively low awareness of social responsibility dampens the enthusiasm of non-state-owned enterprises for technological advancement. Consequently, environmental protection tax policy has a greater influence on the total factor productivity of state-owned enterprises.

TABLE 5 Heterogeneity analysis.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	State	Nonstate	Big	Small	Strong	Weak
Post*Reform*Polluted	0.056**	0.040*	0.047**	0.045***	0.058**	0.045**
	(2.19)	(1.77)	(2.31)	(2.99)	(2.27)	(2.32)
Lev	0.003***	0.003***	0.001	0.003***	0.003***	0.003***
	(3.59)	(5.46)	(1.64)	(6.99)	(5.79)	(5.47)
Roe	0.013	0.004**	0.003	0.004*	0.006*	0.004*
	(1.44)	(2.42)	(1.65)	(1.73)	(1.90)	(2.06)
Liquidity	0.008***	0.005***	0.008***	0.005***	0.006***	0.006***
	(10.28)	(8.44)	(9.68)	(7.59)	(7.49)	(7.73)
LargestHolderRate	0.005***	−0.003**	−0.000	−0.003**	0.002*	−0.001
	(3.14)	(−2.57)	(−0.42)	(−2.49)	(1.77)	(−1.06)
Constant	−1.155	3.008	5.072*	7.032**	1.830	2.626
	(−0.24)	(1.17)	(1.97)	(2.37)	(0.52)	(0.77)
Observations	6,564	14,347	10,949	10,964	11,959	9,954
R-squared	0.248	0.224	0.224	0.172	0.230	0.214
Number of Stkcd	1,250	3,182	2,320	2,961	2,409	1,970
Year FE	YES	YES	YES	YES	YES	YES
Pid*Year FE	YES	YES	YES	YES	YES	YES
Industry*Year FE	YES	YES	YES	YES	YES	YES
Industry*Pid FE	YES	YES	YES	YES	YES	YES

Robust t-statistics in parentheses,***$p < .01$, **$p < .05$, *$p < 0.1$.

5.2.2 Heterogeneity in scale

This paper uses the median asset size as the quantile point and splits the entire sample into two subgroups: large-scale and small-scale businesses. In columns (3) and (4) of Table 5, the regression results for the two subsamples are displayed. In general, the effect of environmental protection tax on the total factor productivity of enterprises is stable across the two subsamples, and the coefficients are not significantly different, indicating that enterprises of various sizes are affected similarly by environmental protection tax policy. Nevertheless, it has a higher effect on the total factor productivity of big enterprises. This could be due to the fact that larger companies have scale advantages and superior technical capabilities, which are beneficial for innovative technology research and development. Due to the fact that smaller companies have inadequate technological capabilities and have greater resource constraints, it is challenging for them to engage in technological innovation.

5.2.3 Heterogeneity in strength of environmental law enforcement

The implementation of the environmental protection tax, despite being authoritative and mandatory, non-etheless requires a robust legal framework. Environmental law enforcement represents the degree to which local governments are concerned about environmental issues. In general, a higher level of environmental law enforcement can make environmental policies more fully implemented and improve their performance. In order to investigate the heterogeneity of the impact of the environmental protection tax system on the total factor productivity of enterprises under different environmental law enforcement efforts, in this paper, the ratio of the frequency of words related to "environmental protection" in provincial government work reports to the number of words in the full text of the reports is taken as the proxy variable of environmental governance. On the one hand, it can reflect the government's efforts in environmental governance, and on the other hand, it can alleviate endogenous problems. Local government work reports are generally released at the beginning of the year, while economic activity runs throughout the year. The samples are divided based on the number of environmental governance word frequency in the year preceding the implementation of the environmental protection tax policy (2017). Regions with lower environmental law enforcement intensity are those where the number of environmental governance word frequency is less than the median value, and provinces with higher environmental law enforcement intensity are those where the number of environmental governance word frequency is equal to or greater than the median value. The regression findings for the two subsamples are displayed in columns (5) and (6) of Table 5. In regions where environmental law enforcement is more stringent, the environmental protection tax system has a stronger impact on the total factor productivity of enterprises. This could be due to the fact

that if companies are located in regions with weaker law enforcement, they are less likely to be punished for emissions violations. As a result, the incentive for innovation research and development and resource allocation upgrades is diminished, and the policy's impact is limited.

6 Conclusion

China's modernizing progress is contingent on achieving harmony between humanity and nature. Using China's environmental protection tax policy reform as a natural experiment, this paper empirically investigates the influence of environmental protection tax on the total factor productivity of firms using the triple difference approach. The study concludes that the implementation of an environmental protection tax substantially increases the total factor productivity of listed companies. Further investigation reveals that total factor productivity can be enhanced primarily through two routes: increasing the level of technical innovation and optimizing resource allocation. Analysis of heterogeneity suggests that state-owned enterprises, large businesses, and regions with stronger enforcement of environmental laws are more responsive to environmental protection tax policies.

This paper concludes the following policy implications based on these findings. First, the environmental protection tax reform has a positive policy effect, demonstrating that China's use of market mechanisms to regulate environmental pollution within the context of high-quality economic development is beneficial. We should continue to optimize and improve the tax system for environmental protection and create more fair taxation scope and tax rate criteria. Simultaneously, the enforcement of environmental taxes should be strengthened, the relationship between the government and the market should be properly managed, and the intervention of local governments should be reduced. Second, when implementing and regulating environmental economic tax laws, the varied characteristics of enterprises and areas must also be taken into account. Emphasis must be placed on increasing the supervision of high-pollution and high-emission industries, enhancing policy guidance, and helping small and medium-sized businesses. Lastly, companies should be encouraged to take the initiative to implement strategic reform through technological innovation and factor structure adjustment in order to rationally address environmental protection tax policies.

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

XS designed the research and wrote the manuscript. CZ completed the empirical test and analysis. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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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.

Publisher's note

Supplementary material

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Evaluation and influencing factors of farmers' sustainable livelihood response to ecocultural tourism in minority areas of China

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Ecocultural tourism plays an crucial role in promoting poverty reduction and farmers' sustainable livelihood enhancement worldwide, which has attracted strong attention from scholars and society. However, the impact of ecological and cultural capital of farmers' sustainable livelihoods have not been yet fully investigated. This paper modifies the sustainable livelihoods framework (SLF) and emphasizes the effects of ecological and cultural capital on farmers' sustainable livelihoods. The modified SLF can be used as a possible theoretical model to comprehensively characterize farmers' sustainable livelihoods in tourism destinations with rich ecological and cultural resources. By constructing an evaluation index system, principle component analysis and multiple linear regression are used to analyze the types and response levels of farmers' sustainable livelihoods to ecocultural tourism and determine the factors influencing this response. The results show that farmers' sustainable livelihood responses to ecocultural tourism can be classified into six types. The overall response values are low, and the responses are ranked by the degree of response in descending order as complete response, balanced development, cultural network, ecology-dominant, developmental delay, and resource advantage response. Farmers' sustainable livelihoods respond strongly to cultural capital and ecological capital factors and relatively weakly to physical, natural, social, financial, and labor capital. Five main factors that influence farmers' sustainable livelihood responses are then identified. Finally, strategies and suggestions for livelihood transformation, strategy selection, and improvement are proposed. This study provides case study examples for promoting the sustainable development of ecocultural tourism sites and improving farmers' livelihoods in China and worldwide.

KEYWORDS

ecocultural tourism, farmers, sustainable livelihood, livelihood response, minority area

Introduction

Poverty is a global challenge that is particularly significant in developing countries (Liu et al., 2017; Rignall et al., 2017). Unlike the rapid expansion of urbanization, rural areas, where 79% of the world's poor live, are gradually declining. Thus, promoting the development of rural economies and improving the livelihood of farmers has become a common goal in global poverty reduction (Guo and Liu, 2021; Li et al., 2021). As a tool for economic growth and diversification, rural tourism can broaden the livelihood channels of families and enrich the livelihood assets of farmers and has become the driving force in local economic development (Mbaiwa, 2011; Zhao et al., 2021). Rural tourism can transform the traditional income sources

of farmers to that of tourism, promote new capital and livelihood strategy combinations, enrich farmers' livelihood diversity, and improve their livelihood resilience (Su et al., 2019; Bires and Raj, 2020). A large number of studies have found that tourism has improved the livelihoods of local people in rural areas and has played a significant role in poverty reduction around the world (Saarinen et al., 2011). For villages with rich natural and cultural resources, making full use of regional resource advantages to develop rural tourism and transform the livelihoods of farmers is a feasible way to promote rural economic development and improve farmers' livelihoods.

Ecocultural tourism has gradually emerged as the leading form of tourism as global concepts of development evolve, and living standards improve. Ecocultural tourism is based on natural ecological endowment and is centered on historical and cultural relics. As a new mode of tourism that promotes sustainability, stability, and harmony, it presents an effective method to achieve sustainable tourism (Guri et al., 2020). Ecocultural tourism is the result of the mutual response of the human economy, culture, and sustainable social development (Guillaume et al., 2017). It plays an important role in promoting environmental protection, cultural inheritance, and economic development by integrating ecological and cultural resources to maximize the economic, social, and ecological benefits of tourism destinations. Research on rural ecocultural tourism involves many diverse disciplines, research fields, and perspectives, which have extended its scope (Ross and Wall, 1999; Cater, 2000; Clifton and Benson, 2006). The research contents have mainly focused on theory and tourism management. Scholars have explained the concept of ecocultural tourism from different perspectives and discussed the feasibility and rationality of ecocultural tourism as a method to achieve sustainable development in culturally vulnerable and ecologically sensitive areas (Wallace and Russell, 2004). They have also combined ecocultural tourism with tourism development, decision-making, cultural heritage, and sustainable development (Guillaume, 2019; Sun, 2020). Additionally, scholars have carried out detailed research on the factors influencing ecocultural tourism and environmental protection, determining that the reasonable and effective development of ecocultural tourism can predominantly be obtained through resource integration (Jamal et al., 2010; Tiberghien et al., 2017). The research methods focused on case studies, combining qualitative description and quantitative evaluation methods to build an analysis framework and evaluation indicators. Case studies were conducted in tourism destinations in Europe, Asia, Africa, and other regions through induction and deduction, providing tourism practitioners with new concepts for development and management (Guillaume et al., 2020; Guri et al., 2020). The recent collaborative study of ecocultural tourism and poverty, sustainable livelihood, regional development, and other issues has facilitated a new era in ecocultural tourism, which is of great significance to the politics, economy, and individual livelihoods of countries around the world.

The World Commission on Environment and Development (WCED) first put forward the concept of sustainable livelihood in 1980, which comprehensively considered various factors affecting poverty and provided a new perspective for solving the world poverty problem (DFID, 2000). Chambers discussed the connotations of sustainable livelihood, considering a sustainable livelihood as one that could recover from pressure and influence, maintain or strengthen its capacity and assets over time, and not damage the natural resource base (Chambers and Conway, 1992). Due to different academic backgrounds and research objects, there are many analytical frameworks for understanding and evaluating sustainable livelihoods, among which the sustainable livelihood approach (SLA) framework established by the British Agency for International Development (DFID) is widely used (Carney, 1998). The SLA framework takes the fragile environment and the process of policy institutions as the analysis background, regards poor families as the main earners in the fragile environment, and reveals the mechanism of sustainable livelihoods by linking livelihood assets, strategies, output, and other factors (Toner and Franks, 2006). It is a model for understanding poverty, which identifies the potential opportunities for poverty eradication, and reveals how people use a large number of properties, rights, and strategies to pursue a certain livelihood. Sustainable livelihood research focuses on how human beings survive and maintain their sources of income and is widely used to study the human dimension of development issues and global change (Savari and Moradi, 2022). Scholars have explored the risks of vulnerable environments to farmers' livelihoods (Thuy et al., 2022; Ye et al., 2022) and the adaptability of farmers to such risks (Chen et al., 2021; Tran et al., 2021). An evaluation system was constructed to carry out a quantitative analysis of farmers' livelihood assets (Wang et al., 2021), analyze the factors affecting farmers' these assets (D'Annolfo et al., 2021), and propose countermeasures to promote their optimization and transformation (Sivagnanam et al., 2019). The impact of policy and regulation implementation on the livelihoods of farmers was also analyzed as a basis to test the effect of past measures and guide the formulation of future decisions (Barati et al., 2021; Su et al., 2021). The causes, constraints, existing problems, and change prospects of farmers' livelihood strategies and sources and characteristic trends of livelihood diversification were explored (Mao et al., 2020) to guide farmers to flexibly switch among various livelihood strategies to maintain their livelihood security (Mao et al., 2020). Research on farmers' livelihood restoration (Li et al., 2019) and sustainable livelihood response has also gradually emerged in recent years (Savari and Zhoolideh, 2021). Villages have undergone adaptive adjustment and continuous evolution under the disturbance of internal and external factors, which has had an important impact on the sustainable livelihood of farmers. The mutual feedback between farmers and communities has also promoted the evolution of rural adaptation. Scholars explored the livelihood changes and responses of farmers in the context of policy change, social transformation, industrial poverty alleviation, rural evolution, *etc.* (Ding et al., 2020; Su et al., 2021.; Bogale et al., 2022). They have also analyzed the livelihood responses of farmers with different livelihood modes to changes in the external environment (Ding et al., 2019; Su et al., 2019), which played an important role in the sustainable development of farmers' livelihoods.

As the participants and stakeholders of rural ecocultural tourism, the development of rural ecocultural tourism will disturb the types and strategies of farmers' livelihoods (Stastna et al., 2020; Sun et al., 2021). Researchers are beginning to address issues regarding the types of sustainable livelihood responses farmers have to rural ecocultural tourism, how and to what degree their response levels change, and the major factors influencing this. These problems have gradually formed new perspectives for studying sustainable rural development. China is the largest developing country in the world, with a high number of villages and rural populations. Poverty is a significant issue hindering China's sustainable development. As China is rich in natural

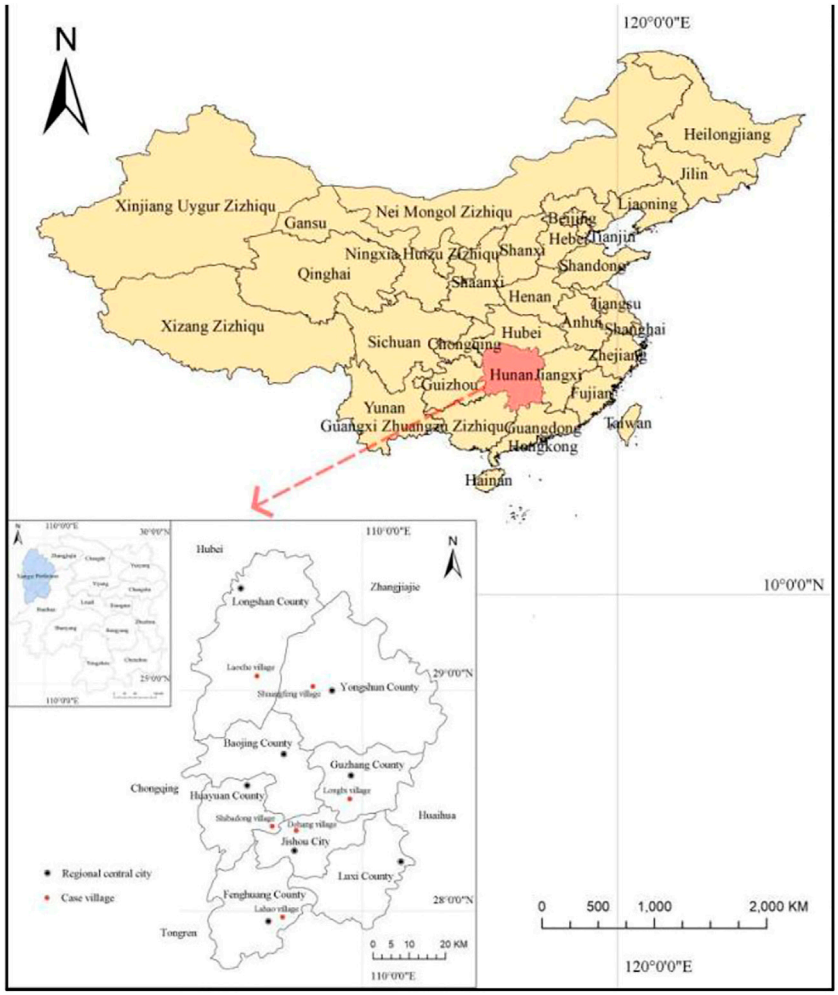

FIGURE 1
Location map of six villages.

and cultural resources, rural ecocultural tourism plays an important role in China's socioeconomic development and is an effective way to alleviate industrial poverty alleviation and revitalize rural areas. However, many problems exist in the process of rural tourism development in China, such as unbalanced regional development, low economic benefits, and low participation of farmers, which seriously hinder rural development. In addition, similarly to many tourism destinations, China's tourism development is largely promoted by external stakeholders, such as the government and tourism companies. As a result, residents are excluded from the decision-making process of rural tourism, posing a serious threat to farmers' livelihoods.

While most of the current studies on farmers' sustainable livelihood are based on the SLA framework, this model is not suitable for direct application in ethnic areas (Quandt et al., 2018; Ma et al., 2021). Farmers' sustainable livelihoods present strong regional and subjective characteristics, and ecological capital, cultural capital, and subjective behavior also have important impacts (MacRae, 2017; Alipour et al., 2021). However, the SLA framework has been criticized for ignoring the power inequality among different stakeholders. Therefore, this paper modifies the SLA framework used to study ecocultural tourism by emphasizing the role of ecological and cultural factors in influencing farmers' sustainable livelihoods in ethnic areas. The modified framework is used to analyze the types of livelihood responses and influencing factors of such livelihoods to ecocultural tourism in ethnic areas of China. This study provides case studies for the development of ecocultural tourism and improving farmers' sustainable livelihood worldwide. The problems and shortcomings of ecocultural tourism development in ethnic areas are also identified, and effective suggestions for the implementation of rural revitalization strategy in China and globally are presented.

Data and methodology

Study area

This paper takes the most representative ethnic regions in China as the research area. Xiangxi Prefecture is located in the northwest of Hunan Province, China. It is a national cultural and ecological protection and national tourism demonstration area, with rich

TABLE 1 Analysis of resources in the six villages.

Village	Landscape and resources	Cultural resources	Feature industries	Honorary names
Shuangfeng Village	Baishou Hall and ancient trees	Longfeng flag raising, ancestor worship, Tujia Daliuzi, wood leaf blowing, bride's weeping songs, Tujia Maogusi dance, and hand-waving dance	Tea growing and bee breeding	The first Tujia village in China
Lahao Village	Beacon towers, Southern Great Wall Lahao Yingpan section, and Shiban Village	Stonework, woodwork, and Miao medicine	Kiwi growing	A key cultural artifact protection unit of China and one of the first traditional ancient villages of China
Dehang Village	Stilt houses and canyon scenery	Miao songs, Miao dance, lion snatching, knife ladder climbing, bull racing, gate blocking and antiphonal singing challenge, and toasting	Tourism	Province-level scenic and historic area; national key scenic and historic area
Laoche Village	Tujia Chongtian buildings and Rebala Tujia pavilion bridge	Ceremonial weeping for marriage, hand-waving dance, Maogusi, Daliuzi, Dongdongkui, and dragon boat race	Ecotourism agriculture and goat and cattle farming	Chinese national culture and art, the hometown of Tujia brocade
Longbi Village	Morong Miao Village	Miao drum dance and Miao folksongs	Tourism and tea growing	Hometown of the Miao flower drum, hometown of Chinese folk culture and art, and Chinese traditional village
Shibadong Village	Miao Village scenery	Watermelon festival, dragon dance, knife ladder climbing, cattle slaughter, and Miao song singing	Tourism and plantation industry	Chinese traditional village

natural and cultural resources that provide the basis for ecocultural tourism development. Xiangxi Prefecture has a subtropical monsoon climate and abundant water resources. The major rivers are the Yuan, You, Wu, and Mengdong Rivers (Figure 1). Because Xiangxi Prefecture has abundant wood resources, wooden Tujia-style houses with Xiangxi characteristics are extremely common. Xiangxi Prefecture is one of the most famous ethnic regions in China. The population of ethnic minorities accounts for 77.21% of the total population of the prefecture. Xiangxi Prefecture has a World Heritage Site, 12 national key cultural artifact protection units, 12 Hunan Province cultural artifact protection units, and 11 A-class scenic spots. The area has rich natural landscape resources and cultural sites, which provide a basis for tourism development. In the past, Xiangxi Prefecture was economically backward and belonged to a poor area because of its remote location. However, with the support of the national tourism poverty alleviation policy, it has vigorously developed ecological cultural tourism to promote regional economic development. At present, 181 villages in Xiangxi Prefecture have carried out tourism development. Ecocultural tourism has become the pillar industry of Xiangxi Prefecture and the most effective way to promote farmers' sustainable livelihoods.

We conducted ecocultural tourism field research in Xiangxi Prefecture, considering village roads, traffic, village features, population, economic performance, and industry scale. Six ecocultural tourism villages were selected for the survey: Yongshun County's Shuangfeng Village, Fenghuang County's Lahao Village, Jishou City's Dehang Village, Longshan County's Laoche Village, Guzhang County's Longbi Village, and Huayuan County's Shibadong Village. A location map of these villages is provided in Figure 1 and Table 1 presents an analysis of their resources. These villages are selected as case studies as they are rich in natural and cultural resources and have the characteristics and manifestations of ecocultural tourism villages, such as traditional buildings, customs, and costumes, as well as natural scenery, which are suitable for the development of rural ecocultural tourism. Secondly, the development of ecocultural tourism in these villages has increased the annual *per capita* income of farmers from less than 2000 yuan (300 US dollars) to 15,000 yuan (2500 US dollars), alleviating poverty in these areas. Thus, it can be observed that the ecocultural tourism industry has had a profound impact on farmers' sustainable livelihood, with high social awareness and economic benefits. Finally, these villages include different tourism development models (government-led development, tourism enterprise-led development, village-led development) and farmers of different livelihood types, which largely represent the livelihood characteristics of ecocultural tourism farmers in ethnic areas.

Data resources

A variety of data collection methods were adopted to ensure the richness of information, improve the credibility and preciseness of the research, and promote a triangular relationship between methods and research effectiveness (Baxter and Eyles, 1996). First, the basic information of the six villages was obtained through the official websites and policy documents of the local governments. Field research was then carried out in the six villages from July to September 2022. These included structured questionnaires and semi-structured interviews, as well as farmers' livelihood data, which was obtained in detail. The survey content mainly included the livelihood capital of farmers and their participation in and attitude toward ecocultural tourism. Farmers and families were considered as a unit, and the survey time for each household was 45–60 min. The interviewees were mainly the heads of households or the main labor force of families, and they could refuse to answer any questions that were uncomfortable for them (Liu et al., 2022). This part of the survey was mainly achieved through snowball sampling (Baxter and Eyles, 1996). First, we conducted a detailed interview with the main leaders of each village and asked for referrals after the interview. As the snowball sampling method may be affected by self-selection bias, we also conducted a random sampling survey of farmers to overcome these limitations and ensure data objectivity. In addition, researchers lived with villagers and learned about ecocultural tourism from their

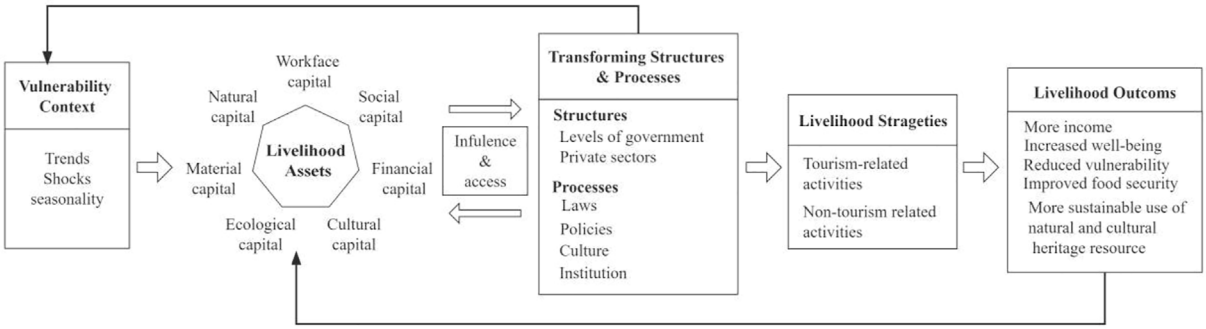

FIGURE 2
Sustainable livelihood framework for ecocultural tourism [adapted from the DFID. (2000)].

perspective, including farmers' daily livelihood behavior and how they participate in rural tourism activities. A total of 350 questionnaires were issued, and 350 were returned. After removing the missing and abnormal values of key variables, 327 valid farmers' sample data were finally obtained, accounting for 93.4% of the sample. The number of questionnaires in each village was more than 50, meeting the requirements for reliability, validity, and representativeness of data.

Theoretical framework and evaluation index system

SLF is a practical tool that is widely used in the analysis of farmers' livelihood diversity and regional poverty reduction. The framework includes five concepts: fragile environment, livelihood assets, transformation structure and process, livelihood strategy, and livelihood results (Scoones, 1998; DFID, 2000). Among them, livelihood assets are the ability to build livelihoods and resist livelihood risks and the rights forming the basis of livelihood strategy selection. The background of vulnerability refers to the external environment composed of specific conditions, trends, shocks, *etc.*, which affects the availability and controllability of assets. Livelihood strategies are the activities and choices to achieve livelihood goals, while livelihood output is the yield and results of engaging in livelihood strategies. Policies, institutions, and processes refer to the systems, organizations, policies, and relevant legal norms that affect livelihoods, which will influence the exchange conditions between different types of capital and the choice of livelihood strategies.

While SLF provides standardized tools and systematic research concepts for the study of farmers' livelihoods, it still has some limitations in the context of ecocultural tourism (Liu et al., 2022). First, it ignores the important value of cultural factors on farmers' sustainable livelihoods. Especially in ethnic areas where tourism is developed, traditional culture is an important factor in increasing tourism attraction and promoting the sustainability of farmers' livelihoods (Daskon and Binns, 2010). As such, cultural factors should be included in SLF as important livelihood capital. Secondly, SLF does not fully consider farmers' community participation and sustainable livelihood responses. (Shen, et al., 2008). For ethnic villages, ecocultural tourism is not only responsible for economic development but also for cultural heritage and ecological protection, in which farmers play a key role (Quandt, 2018). Tourism development has affected the livelihood assets of farmers and also led to changes in their livelihood behavior. These changes are mainly reflected in the ecological behavior of farmers. Therefore, it is also necessary to include the ecological capital of farmers in the analysis (Wang, et al., 2014). The modified SLF, with the additions of "cultural capital" and "ecological capital," is shown in Figure 2. On this basis, the sustainable livelihood response index system of farmers' ecocultural tourism is constructed to improve the reliability of the evaluation results.

Investigation of farmers' sustainable livelihood responses to ecocultural tourism in minority areas requires consideration of a clear subject, sustainable livelihood participants, and the means through which farmers can achieve such livelihoods. Farmers' sustainable livelihoods are a crucial issue for rural revitalization through the development of rural ecocultural tourism. Tourism disturbance affects the livelihood of farmers, prompting them to choose livelihood strategies or change their livelihood methods. The livelihood capital owned by farmers provides the basis for farmers to resist livelihood risks and formulate livelihood strategies. The types, levels, and factors of farmers' sustainable livelihood responses are analyzed based on the theory of sustainable livelihood and combined with the actual situation of the study area. These data are then employed to construct an evaluation index system of sustainable livelihood responses of farmers' ecological and cultural tourism in Xiangxi Prefecture from the perspective of farmers' livelihood capital response with seven primary indicators and 23 secondary indicators (shown in Table 2).

The seven criterion-level indicators are natural, material, financial, workforce, social, ecological, and cultural capital. Natural, material, social, workforce, and financial capital are the five basic livelihood capitals in the study of the sustainable livelihood of farmers, which are universal elements of farmers' livelihoods. Ecological capital is the ecological endowment that farmers can use to develop ecocultural tourism and is also the main basis forming the appeal of rural tourism. Cultural capital is the unique essence of ecocultural tourism development and the core of constructing ecocultural tourism characteristics. Together, they constitute the resource background for the rural development of ecocultural tourism. The "high-speed" development of industry, workforce, organization, ecology, and culture requires the support of the corresponding five major basic types of livelihood capital to

TABLE 2 Indicator system of farmers' sustainable livelihood responses to rural ecocultural tourism.

Criterion level	Indicator level	Variable evaluation	Sub-weight	Total weight
Natural capital B_1 (0.0833)	Agricultural land area (C_1)	1 = less than 0.066 h m^2; 2 = 0.067–0.133 h m^2; 3 = 0.134–0.198 h m^2; 4 = 0.199–0.264 h m^2; 5 = more than 0.265 h m^2	0.1667	0.0139
	Homestead area (C_2)	1 = less than 0.033 h m^2; 3 = 0.034–0.066 h m^2; 5 = more than 0.067 h m^2	0.8333	0.0694
Material capital B_2 (0.0916)	House area (C_3)	1 = less than 100 m^2; 2 = 100–200 m^2; 3 = more than 200 m^2	0.1048	0.0096
	House type (C_4)	1 = stone; 2 = wood; 3 = brick and wood; 4 = brick and concrete	0.4991	0.0457
	Major furniture items in the house (C_5)	1 = less than 20,000 CNY; 2 = 20,001–30,000 CNY; 3 = 30,001–40,000 CNY; 4 = 40,001–50,000 CNY; 5 = more than 50,001 CNY	0.3961	0.0363
Financial capital B_3 (0.0953)	Part-time work income (C_6)	1 = less than 10,000 CNY;; 2 = 10,001–20,000 CNY;; 3 = 20,001–40,000 CNY; 4 = 40,001–60,000 CNY; 5 = more than 60,001 CNY	0.0821	0.0078
	Tourism income (C_7)	1 = less than 3000 CNY; 2 = 3,001–6000 CNY; 3 = 6,001–10,000 CNY; 4 = 10,001–15,000 CNY; 5 = more than 15,001 CNY	0.5498	0.0524
	Rural tourism investment fund (C_8)	1 = under 5000 CNY; 2 = 5,001–10,000 CNY; 3 = 10,001–20,000 CNY; 4 = 20,001–30,000 CNY; 5 = more than 30,001 CNY	0.3681	0.0351
Workforce capital B_4 (0.0494)	Migrant labor or start-up experience (C_9)	1 = none; 2 = 1 time; 3 = 2 or 3 times; 4 = 3–5 times; 5 = more than five times	0.0852	0.0042
	Number of family members participating in tourism (C_{10})	1 = 1; 2 = 2; 3 = 3; 4 = 4; 5 = 5 or more	0.6442	0.0318
	Number of relatives and friends (C_{11})	1 = fewer than 50; 2 = 51–100; 3 = 101–150; 4 = 151–200; 5 = more than 201	0.2706	0.0134
Social capital B_5 (0.0338)	Residence location (C_{12})	1 = more than 201 m from the main road of the village; 2 = 101–200 m away; 3 = 51–100 m away; 4 = within 50 m; 5 = next to the main road	0.0737	0.0025
	Frequency of professional skill training (C_{13})	1 = none; 2 = 1 time; 3 = 2 or 3 times; 4 = 4 or 5 times; 5 = more than five times	0.1873	0.0063
	Family members participating in social affairs (C_{14})	1 = no participation; 2 = 1 time; 3 = 2 times; 4 = 3 times; 5 = more than three times	0.2851	0.0096
	Closeness to related organizations (C_{15})	1 = none; 2 = 1 time per month; 3 = 2 or 3 times per month; 4 = 4 or 5 times per month; 5 = more than five times per month	0.4539	0.0153
Ecological capital B_6 (0.2839)	Clean energy usage level (C_{16})	1 = firewood; 2 = coal or charcoal; 3 = electricity; 4 = liquefied gas or biogas; 5 = solar power	0.1469	0.0417
	Average expenditure and pesticide cost per mu of land (C_{17})	1 = more than 51 kg; 3 = 31–50 kg; 5 = less than 30 kg	0.1469	0.0417
	Domestic sewage processing method (C_{18})	1 = discharge at will; 2 = sewage is sometimes reused; 3 = sewage is often reused; 4 = sewage is collected without harmless treatment; 5 = sewage is collected with harmless treatment	0.548	0.1556
	Human and animal feces processing method (C_{19})	1 = discharge at will (without septic tank); 2 = some feces is used as fertilizer (without septic tank); 3 = all feces is used as fertilizer (without septic tank); 4 = individual treatment with septic tank; 5 = centralized treatment with septic tank	0.1583	0.0449
Cultural capital B_7 (0.3627)	Folk art and cultural performance participation level (C_{20})	1 = none; 2 = individual festivals; 3 = important festivals; 4 = most festivals; 5 = all festivals	0.3153	0.1143
	Traditional farming tool preservation level (C_{21})	1 = abandoned farming; 2 = no traditional farming tool; 3 = traditional farming tools (fewer); 4 = traditional farming tools (more); 5 = complete traditional farming tools	0.0602	0.0218
	Frequency of wearing ethnic clothing (C_{22})	1 = no ethnic clothing; 2 = wear rarely; 3 = wear to festival events (less); 4 = often wear (more); 5 = always wear	0.0843	0.0306
	Ethnic buildings (C_{23})	1 = building with ethnic elements (no conservation); 2 = renovation (keeping ethnic elements); 3 = ethnic building (poorer conservation); 4 = ethnic building (average conservation); 5 = ethnic building (superior conservation)	0.5402	0.1959

achieve the "high-quality" development of ecocultural tourism. Research on farmers' sustainable livelihood response can guide farmers to make reasonable choices that are practical and incur lower risks when affected by ecocultural tourism or other disturbances to livelihood. Thus, farmers can achieve the steady development of their sustainable livelihoods and promote the orderly implementation of rural revitalization strategies through their responses to ecocultural tourism.

TABLE 3 Total variance of interpretation.

Component	Initial eigenvalue			Extraction load sum of squares		
	Total	Percentage of variance	Cumulative percentage	Total	Percentage of variance	Cumulative percentage
1	3.479	16.255	16.255	3.479	16.255	16.255
2	2.120	10.346	26.601	2.120	10.346	26.601
3	1.953	9.622	36.223	1.953	9.622	36.223
4	1.727	9.041	45.864	1.727	9.041	45.864
5	1.563	8.427	53.691	1.563	8.427	53.691
6	1.488	7.601	61.292	1.488	7.601	61.292
7	1.323	7.184	68.476	1.323	7.184	68.476
8	1.231	6.282	74.758	1.231	6.282	74.758
9	1.065	5.312	80.070	1.065	5.312	80.070
10	0.977	4.046	84.116	—	—	
11	0.949	3.125	87.241	—	—	
12	0.826	2.890	90.131	—	—	

Methods

The participatory rural appraisal method was employed for field research on rural ecocultural tourism in Xiangxi Prefecture. The Delphi method, analytic hierarchy process, and expert grading method were used to determine the weights of 23 indicators, including agricultural land areas (Wang, et al., 2021). Principal component analysis was used for dimension reduction of the 23 indicators, which were transformed into nine comprehensive indicators, and the principal components were extracted for analysis (Wu, et al., 2018). To determine the types of response of farmers to ecocultural tourism in Xiangxi Prefecture, cluster analysis was used to analyze the nine comprehensive indicators, and six livelihood response types, such as the balanced development type, were identified. Stepwise analysis was then employed to analyze the elements (Wu, et al., 2020). Tourism income was used as the dependent variable, and other factors were used as the independent variables. Finally, the factors affecting farmers' response to sustainable livelihood were analyzed.

Results

Response types of farmers' sustainable livelihood

Main factor extraction

Statistical analysis was conducted using the interview data, and principal component analysis was carried out using SPSS 24.0 statistical software on the questionnaire survey data from the residents of the six case villages. The Kaiser-Meyer-Olkin test result was 0.676, indicating strong correlations between the variables. Bartlett's sphericity test result was close to that of the chi-square test, at 1273.001. The number of degrees of freedom was 253, and the significance value was smaller than 0.05. This indicated that the variables were not independent and significant correlations existed between them. The data were thus suitable for factor analysis. The nine major factors extracted using principal component analysis were also independent, meaning the extracted factors had a favorable quality (Table 3). Through further analysis, the nine major factors were identified as economic development, infrastructure, social development, folk culture, economic ecology, social connection, natural resources, policy awareness, and ecological development factors.

Classification of response types

Classification of farmers' sustainable livelihood response types can aid in developing rural ecocultural tourism, implementing rural revitalization strategies, and the targeted formulation of agriculture policy by the government. It can also help to increase land use efficiency and improve ecological environment conservation. K-means cluster analysis was performed in this study for classification according to the sustainable livelihood data obtained from 327 farmer households. The final cluster center table (Table 4) shows that in cluster 1, the scores were highest for the infrastructure (0.92272) and social development (1.03942) factors. The average factor score was balanced among the six types, reflecting the "balanced development type." In cluster 2, the economic development factor had the highest score (2.03796). The remaining infrastructure (0.09503), economic ecology (0.31390), social connection (0.53024), policy awareness (0.39001), and ecological development (0.05978) factors also had high scores, which reflected the "complete response type." In cluster 3, the ecological development factor had the highest score (1.74162). In addition, the natural resource factor had a relatively high score (0.23359), so this type was considered the "ecology-dominant type." In cluster 4, the folk

TABLE 4 Final clustering center table.

Variables	Clustering					
	1	2	3	4	5	6
Economic development factor	−.13080 (2)	2.03796 (1)	−.25674 (4)	−.53618 (6)	−.37178 (5)	−.14663 (3)
Infrastructure factor	.92272 (1)	.09503 (2)	.02232 (3)	−.06678 (5)	−.47604 (4)	−.06863 (6)
Folk culture factor	.00687 (2)	−.00481 (3)	−.19959 (4)	2.85872 (1)	−.20411 (5)	−.26392 (6)
Social development factor	1.03942 (1)	.07022 (3)	−.10153 (4)	.28007 (2)	−.36355 (6)	−.21661 (5)
Economic ecology factor	−.12545 (5)	.31390 (2)	.04047 (4)	.10824 (3)	.65471 (1)	−.69482 (6)
Social connection factor	−.71710 (6)	.53024 (2)	−.32839 (5)	.67530 (1)	−.14690 (4)	.33708 (3)
Natural resource factor	.02393 (4)	−.09842 (5)	.23359 (2)	.11102 (3)	.25878 (1)	−.36067 (6)
Policy awareness factor	.06154 (3)	.39001 (2)	−.07073 (5)	−.03419 (4)	.46524 (1)	−.55644 (6)
Ecological development factor	−.32260 (4)	.05978 (2)	1.74162 (1)	−.04338 (3)	−.50179 (6)	−.38530 (5)

TABLE 5 Classification of farmers' livelihood responsiveness.

Response value	≤1.50	1.51–2.00	2.01–2.50	2.51–3.00	3.01–3.50	≥3.51
Response level	Absolutely no response	No response	Generally no response	General response	Strong response	Complete response

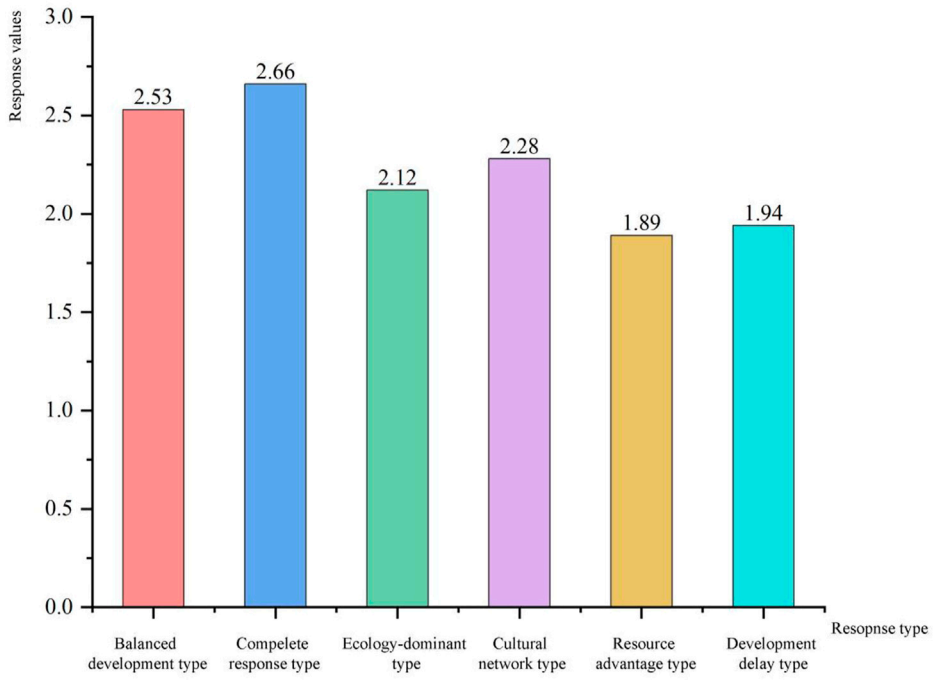

FIGURE 3
Overall responsiveness for the six types of farmers' sustainable livelihood response types.

culture (2.85872) and social connection (0.67530) factors had high scores and were deemed the "cultural network type." In cluster 5, the economic ecology (0.65471) and natural resource (0.25878) factors had high scores, which reflected the "resource advantage type." In cluster 6, the infrastructure (−0.06863), folk culture (−0.26392), economic ecology (−0.69482), and policy awareness (−0.55644) factors had the lowest scores and were considered the "developmental delay type."

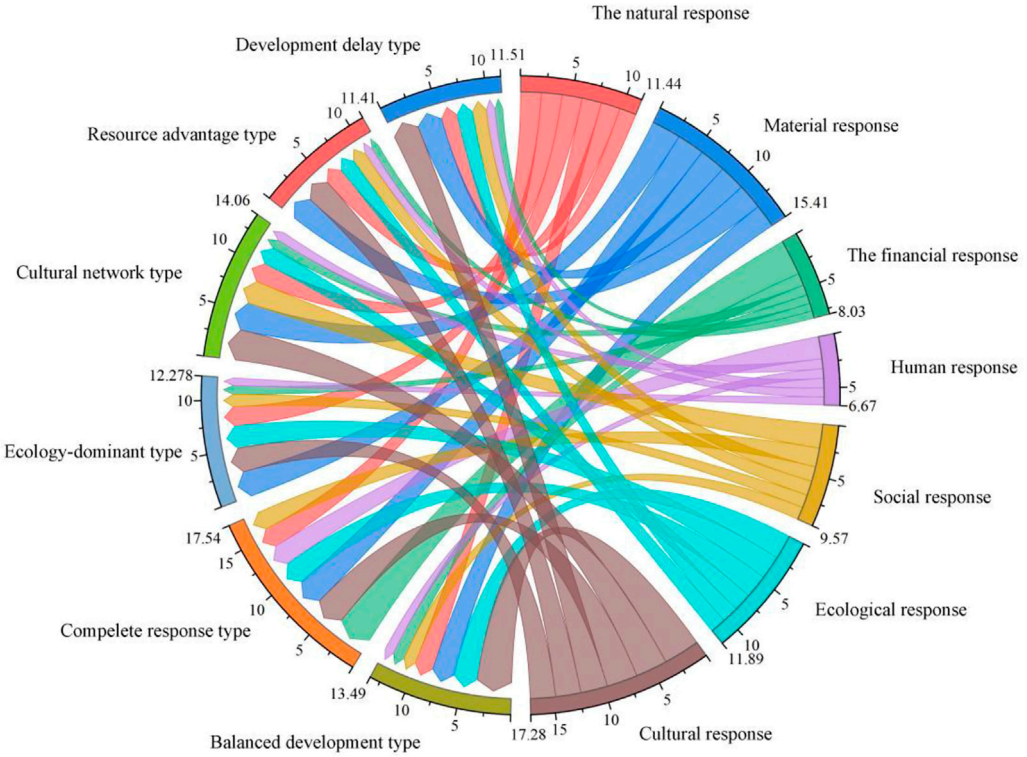

FIGURE 4
Degree of response of different response type factors.

Evaluation of farmers' responses to sustainable livelihood

Indicator weight calculation

The weight survey table was generated using the indicator evaluation system constructed in this study. The survey tables were rated by experts in ecocultural tourism, scholars with relevant backgrounds, and major planners at the planning bureau. The survey table was evaluated using the analytic hierarchy process and the Delphi method (expert grading method), and the weight ratios of the indicators were calculated (Table 2).

The response values were classified using the arithmetic classification method and the 5-point Likert scale. Farmers' sustainable livelihood values were classified into "absolutely no response," "no response," "generally no response," "general response," "strong response," and "complete response" (Table 5).

Overall response level analysis for different response types

The overall response values of the six response types were calculated according to the indicators, and the response levels were determined through evaluation (Figure 3). The order of the overall response values, from high to low, was as follows: complete response type, balanced development type, cultural network type, ecology-dominant type, developmental delay type, and resource advantage type. The overall response values of the six response types were between 2.01 and 2.50; thus, the response levels had generally no response. The response value of the complete response type was higher than 2.51; therefore, the response level was general response. The response values of the balanced development, ecology-dominant, and cultural network types were between 2.01 and 2.50, indicating generally no response. The response values of the resource advantage and developmental delay types were between 1.51 and 2.00, indicating no response.

Response level analysis of different response type factors

Certain similarities and dissimilarities were found in the response levels of the six response type factors (Figure 4). Regarding the natural capital response, farmers with a balanced development response have superior cultural capital but lack human capital. Such farmers have superior cultural capital and ecological capital but lack financial capital and human capital. This is because such farmers lack sufficient funds to participate in ecocultural tourism activities, most of their family workforce choose to go out to work, and tourism participation is low. Although cultural resources are rich, they cannot be converted into economic benefits. Therefore, it is necessary to increase financial support for such farmers and attract more cultural inheritors to participate in ecocultural tourism. Farmers with a complete response type have rich financial capital and cultural capital, and other capital indexes are relatively high without obvious disadvantages. Only social capital and human capital are relatively lacking in this case. Such farmers have good livelihood foundations and diversified livelihood options. As ecocultural tourism is not an important type of livelihood for them, their tourism participation is not high. For such farmers, skills training should be enhanced to encourage participation in

ecocultural tourism. Farmers with an ecology-dominant response type are rich in material capital and ecological capital but are short of other livelihood capital. Such farmers mainly rely on the agriculture and planting industry for their livelihood. While their ecological awareness and behavior are good, the impact of tourism development is very low as they lack the appropriate skills to participate in tourism activities. Of course, such farmers still have certain advantages. In this case, the government and tourism decision-makers should consider them more attentively, provide some financial support, and expand the farmers' source of livelihood by purchasing agricultural products. Farmers with a cultural network response type have rich cultural and material capital, but other capital is relatively lacking. This is because material capital is the basis of their livelihood. Although they can use cultural capital to create income, the overall income level is low, which is an important reason why many young people are unwilling to learn traditional folk culture. Therefore, it is necessary to give more attention and formulate welfare policies for this type of farmer, as well as encourage more young people to learn cultural skills and participate in ecocultural tourism. Farmers with a resource advantage response type are relatively rich in material capital but lack other livelihood capital. Such farmers are typical "Chinese farmers," who are mainly engaged in traditional agricultural production activities and generally have low acceptance of emerging methods. They have a single source of livelihood, with high vulnerability. Thus, the government needs to give them support, and buying their agricultural products could effectively promote their livelihoods. Farmers with a developmental delay response type lack all kinds of livelihood capital. This type of farmer faces poor economic conditions and has an insufficient capacity to carry out livelihood transformation. They not only lack livelihood capital but also need to improve their livelihood awareness. Thus, the government should consider both their material concerns and lack of awareness, as well as establish long-term tracking and security mechanisms to improve their livelihood.

The above comparison indicates that different types of farmers have different responses to various livelihood capital. First, the livelihood assets owned by farmers determine their position in tourism activities (Huang, et al., 2021). Rural tourism requires a certain livelihood basis; Farmers with good family conditions can seize tourism development opportunities and become the main decision-makers or beneficiaries of tourism activities; Farmers with poor family conditions are disadvantaged or unable to participate in tourism activities, perpetuating conditions in which "the poor are poorer, and the rich are richer"(Gautam and Anderson, 2016). Secondly, the livelihood characteristics of farmers determine the way they participate in tourism. Therefore, it is imperative that farmers formulate appropriate livelihood strategies according to their own livelihood characteristics (Dai et al., 2020). For example, farmers with balanced and complete response types should give full play to their livelihood advantages, invest more capital and human resources, and improve their enthusiasm to participate in ecocultural tourism. Farmers with a cultural network response type should fully utilize their cultural advantages, actively innovate forms of cultural expression, and transform intangible cultural resources into tangible cultural capital. Farmers with ecology-dominant and resource-advantage response types should explore new agricultural development models and rely on characteristic agricultural products to improve their livelihood. Of course, the government's support cannot be ignored in this process. It is necessary to provide targeted help to different types of farmers according to local conditions (Liu et al., 2022), especially for farmers with a developmental delay response type. Such farmers should also actively engage in contact with the outside world and transform their perspectives by learning advanced technologies and concepts to improve their livelihood.

Response level analysis of different response factor types

Certain differences were found in the response levels for the seven capital types (Figure 5). Regarding the natural capital response levels, farmers with balanced development, ecology-dominant, resource advantage, or developmental delay response types exhibited no response, and farmers with a complete response and cultural network response type exhibited generally no response. This is because farmers with complete response and balanced development response types have good livelihood bases. Agriculture is not the main source of livelihood, and they are not highly dependent on natural capital. The other four types of farmers have poor livelihood bases and limited natural capital. Therefore, although different farmers have different livelihood conditions, their overall response to natural capital is not high. It is necessary to encourage them to plan and use the homestead and cultivated land. Regarding material capital response levels, farmers with any of the six response types exhibit a general response. This indicates that, in rural ecocultural tourism, these farmers respond to material capital. Farmers' sustainable livelihoods can reach a steady state when disturbed by rural ecotourism. Regarding the financial capital response levels, only the farmers with a complete response type have a general response, and the other five types of farmers have absolutely no response. This result indicates that although ecocultural tourism has greatly improved the livelihood of farmers, the overall livelihood of farmers is still at a low level, and they cannot make large-scale investments in rural tourism. In addition, the low awareness of farmers' participation in tourism is another important reason for the low responsiveness of financial capital. Regarding the workforce capital response levels, only the farmers with a complete response type have generally no response, and the other five types of farmers exhibit absolutely no response. This is because the income most farmers can obtain from rural tourism is limited, and they cannot maintain the daily living expenses of their families. Thus, going out to work is their first choice of livelihood. Therefore, it is necessary to give more employment opportunities to farmers and improve their position in tourism development in order to encourage farmers to actively participate in ecocultural tourism. Regarding the social capital response levels, farmers with a cultural network type have generally no response, and farmers with a complete response type exhibit no response; the other four types of farmers have absolutely no response. The main reason is that farmers' enthusiasm to participate in rural tourism is lacking. Thus, it is necessary to increase the enthusiasm of farmers to participate in social management, strengthen the relationship between farmers and relevant organizations, and provide professional skills training for farmers to improve the sustainability of their livelihoods. Regarding the ecological capital response levels, farmers with a cultural network and resource advantage response type exhibit no response, and the other four types of farmers have generally no response. This result shows that farmers' ecological awareness is relatively weak on the whole, and they should strengthen their environmental awareness, improve their production, living, and tourism facilities, and promote tourism. Such actions can support the adoption of a more technically advanced and reasonable lifestyle to achieve the sustainable

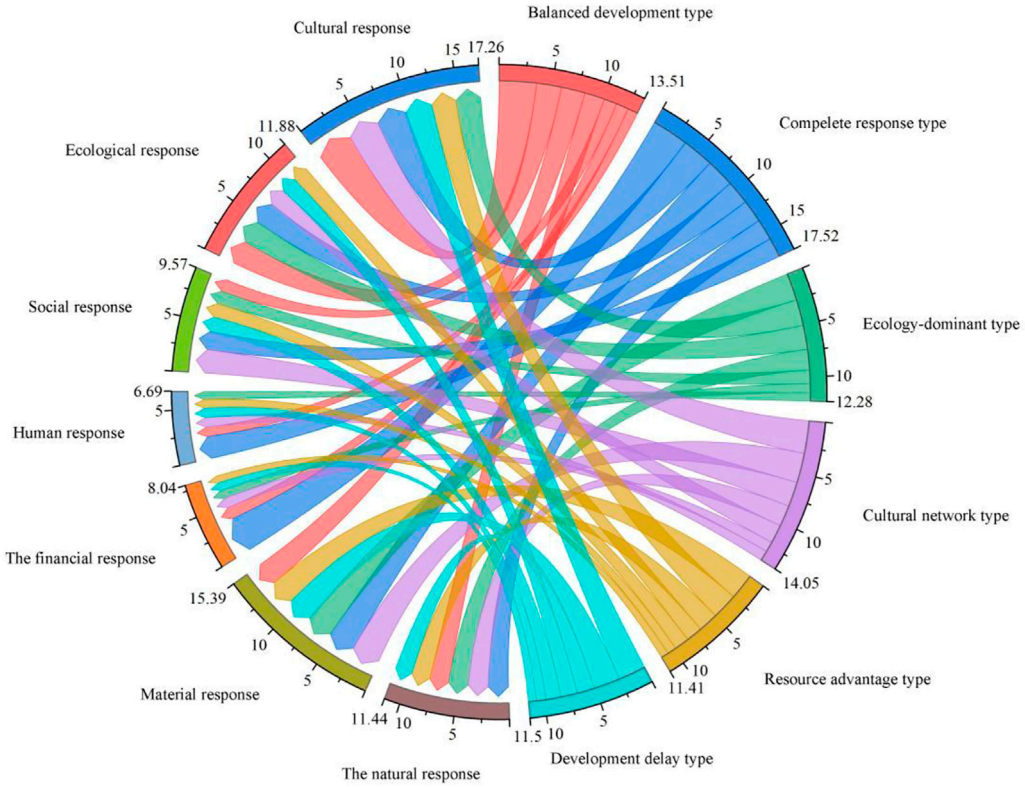

FIGURE 5
Degree of responsiveness of different response factors.

development of rural tourism. Regarding the cultural capital response levels, only the farmers with a resource advantage type response have generally no response, and the other five types of responses are relatively strong. Cultural capital is the unique livelihood foundation of farmers in ethnic areas and a critical resource advantage for developing ecocultural tourism in such areas. Most farmers have mastered these traditional skills. Determining how to make full use of this advantage and transform cultural resources into the source of farmers' livelihood is crucial.

It can be seen from the above comparison that different types of farmers may have the same response form to the same livelihood capital. First, except for cultural capital, farmers' response to the other six types of livelihood capital is relatively low. This is because Xiangxi Prefecture was formerly a poor area, and the overall livelihood level of farmers is not high, meaning the livelihood basis for participating in tourism is limited (Wu et al., 2018). Thus, it is necessary to give financial support to farmers and encourage them to participate in tourism. Secondly, the participation of six types of farmers in tourism is not high. The reason is that the government and tourism enterprises are the main organizers and activity subjects of ecocultural tourism, and farmers are in a disadvantaged position in the process of tourism development (Chen et al., 2020). As they can only obtain a small portion of the benefits, their enthusiasm is reduced. To address this, farmers should be given more rights so that they participate in rural tourism more, profit from it, and their enthusiasm is enhanced. Finally, the gap between the rich and poor is an important issue that cannot be ignored in the development of ecocultural tourism in ethnic regions. While some farmers have better livelihood options and are unwilling to participate in tourism development, most farmers are still in an awkward situation where they want to participate in tourism but have no livelihood basis (Gautam and Anderson, 2016). How to balance the conflict of interest and contradiction between the two groups of farmers is an issue that managers need to pay close attention to.

Scale analysis of factors affecting farmers' responses to sustainable livelihood

Due to the continual development of ecocultural tourism, farmers' responses to sustainable livelihood are no longer influenced by only a single aspect. The tourism industry and other industries are integrated and mutually influencing, disturbing the steady state of farmers' sustainable livelihoods. Therefore, we conducted an analysis targeting the factors affecting the responses to sustainable livelihood of farmers facing ecocultural tourism in Xiangxi Prefecture.

Cluster-dependent variable selection

Tourism income was selected as the dependent variable, the stepwise analysis method was used, and five variables were identified (Table 6). The regression function of farmers' responses

TABLE 6 Statistics in each step of the regression process.

	Model	Non-standardized coefficient		Standardized coefficient	T	Sig
		B	Standard error			
1	(constant)	0.348	0.078		4.476	0
	Number of family members participating in tourism	1.292	0.067	0.732	19.389	0
2	(constant)	0.345	0.074		4.684	0
	Number of family members participating in tourism	1.016	0.078	0.576	13.107	0
	Investment in rural tourism	0.356	0.058	0.27	6.147	0
3	(constant)	0.162	0.116		1.396	0.164
	Number of family members participating in tourism	1.017	0.077	0.577	13.187	0
	Investment in rural tourism	0.327	0.059	0.248	5.512	0
	Number of relatives and friends	0.145	0.071	0.076	2.044	0.042
4	(constant)	0.282	0.126		2.246	0.025
	Number of family members participating in tourism	1.01	0.077	0.572	13.17	0
	Investment in rural tourism	0.335	0.059	0.254	5.669	0
	Number of relatives and friends	0.183	0.072	0.096	2.531	0.012
	Family members participating in social affairs	−0.121	0.051	−0.086	−2.369	0.018
5	(constant)	0.027	0.178		0.154	0.877
	Number of family members participating in tourism	1.015	0.076	0.575	13.298	0
	Investment in rural tourism	0.328	0.059	0.249	5.577	0
	Number of relatives and friends	0.178	0.072	0.093	2.478	0.014
	Family members participating in social affairs	−0.128	0.051	−0.091	−2.513	0.012
	Ethnic buildings	0.078	0.039	0.071	2.013	0.045

[a]Dependent variable: tourism income (Wu, et al., 2020).

to sustainable livelihood based on rural ecocultural tourism is as follows:

$$Y = 1.015X_1 + 0.328X_2 + 0.178X_3 - 0.128X_4 + 0.078X_5 + 0.027 \quad (1)$$

Influence factor analysis

According to the results of Eq. 1, tourism income is influenced by five factors: the number of family members participating in tourism, investment in rural tourism, number of relatives and friends, family members participating in social affairs, and ethnic buildings. The influence on tourism income can be divided into that from strong-influence factors ($\beta \geq 0.3$), moderate-influence factors ($0.1 < \beta < 0.3$), and weak-influence factors ($\beta \leq 0.1$). The number of family members participating in tourism is a workforce capital factor and a strong-influence factor, with $\beta = 1.015$. This factor denotes the number of people in a farming family that work in tourism-related industries, including parents and children. Tourism income is based on the accumulation of funds. The larger the number of participating family members, the more favorable the fund accumulation and the higher the service quality for tourists.

Investment in rural tourism is a financial capital factor and strong-influence factor, with $\beta = 0.328$; it denotes the government's support for rural ecocultural tourism. The development of rural ecocultural tourism must be supported through funding, and a lack of financing limits the development of rural tourism. For rural areas, the larger the fund provided by the government for ecocultural tourism, the higher the rural infrastructure level and the attraction for tourists. The number of relatives and friends is a workforce capital factor and a moderate-influence factor, with $\beta = 0.178$. For tourist attractions, promotions and public reputation are crucial means of attracting tourists, in which word-of-mouth promotion from farmers' families and friends is an essential promotion method. The larger the number of a farmer's family and friends, the larger the range of promotion and the greater the customer flow to tourist attractions.

Family members participating in social affairs is a social capital factor and a weak-influence factor, with $\beta = -0.128$. Ideally, family members work in government institutions, villages, or other social organizations. Thus, the state of tourism and tourist needs can be understood in time through family members' participation in social affairs. Such participation also helps farmers improve their service and management abilities. Ethnic building conservation level is a cultural capital factor and a weak-influence factor, with $\beta = 0.078$. For tourists, the more complete the conservation of ethnic buildings, the more attractive the destination, and the stronger the cultural adaptability of

the tourist attraction. This creates a climate of high cultural conservation awareness and supports rural cultural revitalization. Above all, the workforce, financial, social, and cultural capital factors have the strongest influences on farmers' responses to sustainable livelihood based on rural ecocultural tourism.

Discussion

Formulating methods to simultaneously achieve poverty alleviation and promote the sustainable development of farmers' livelihoods is increasingly crucial as global poverty reduction advances. Since the SLA framework was put forward, the research on the sustainable livelihoods of later-generation farmers has largely considered five aspects of natural, material, workforce, social, and financial capital. However, our field survey illustrates that the traditional five aspects cannot fully summarize the capabilities and assets of farmers. Factors such as ecological resources (Zhao et al., 2021), cultural assets (Ma et al., 2021), religious beliefs (Liu et al., 2014), *etc.*, also have an important impact. The SLA framework should provide an analytical approach to the study of sustainable livelihoods rather than seeking a universal solution. As such, it needs to be revised and adjusted according to the actual situation of the study area and the study object (Zhang and Zhao, 2015). As far as China is concerned, farmers' sustainable livelihood is the result of the joint participation of the government, enterprises, farmers, and multiple other subjects. It involves labor, land, capital, and other key livelihood capital, as well as resource background, policy background, industrial support, and other development conditions. Subjective factors, including farmers' psychology and behavior, also have an important impact (Deng et al., 2020). The main contribution of this paper is to expand ecological and cultural capital on the basis of the five major livelihood capital factors according to the characteristics of minority area ecological and cultural tourism development, as well as the characteristics of farmers' behavior, psychology, and other elements. This provides a more accurate assessment of the livelihood capacity of Xiangxi's farmers and expands sustainable livelihood research. Establishing more comprehensive evaluation indicators and extensively evaluating the farmers' sustainable livelihood response and influencing factors of ecocultural tourism farmers provides theoretical guidance for the implementation of China's rural revitalization strategy and case references for the improvement of farmers' sustainable livelihood in the world's minority areas.

According to our findings, different types of farmers have the same and different responses to livelihood capital in the process of ecotourism development in ethnic areas. On the one hand, ecocultural tourism improves the livelihood capital of farmers (whether farmers demonstrate tourism behavior or not), especially in social capital and financial capital fields (Shui et al., 2022). On the other hand, farmers do not show a strong enthusiasm for ecocultural tourism, which is the result of numerous factors (He et al., 2022). First, due to the limitations of their livelihood foundation, farmers are unable to participate in large-scale tourism investment and lack a sufficient capacity to resist and even adapt to the risks and opportunities brought by tourism interference (Gautam and Anderson, 2016). Second, due to the long-standing inability of farmers to participate in tourism activities, they are at a disadvantage in the competition process with other stakeholders and lack the power and resources to obtain satisfactory returns from tourism activities (Chen et al., 2020). Therefore, how to improve the economic benefits of ecocultural tourism, expand the tourism industry chain, and give farmers more jobs and higher tourism income are issues that deserve special attention.

With the implementation of China's rural revitalization strategy, many non-agricultural businesses have become tourist villages, enriching the diversity of rural farmers' sustainable livelihoods. However, this diversification does not ensure the successful transformation of farmers' livelihood methods. First, as Chinese farmers have been engaged in simple production activities for generations, their livelihood foundation is relatively weak, and their livelihood stability is insufficient. Therefore, they lack adequate funds and the ability to adapt to the livelihood risks caused by tourism interference. Farmers often have low enthusiasm for participating in the process of rural tourism (Chen et al., 2017). It is necessary to guide farmers to actively participate in rural ecocultural tourism, consider expanding the employment channels of rural ecocultural tourism and encourage and guide farmers to start businesses and obtain employment by formulating preferential policies. Farmers' enthusiasm to participate in rural ecocultural tourism should be encouraged to realize the transformation of farmers' sustainable livelihood from labor-oriented to intelligent or service-oriented strategies and inject impetus into the development of rural ecocultural tourism. Secondly, rural revitalization is a major measure involving the participation of all sectors of society, and it is also a significant strategy that best conforms to China's national conditions. While the government has issued many policies to promote rural development, there are still some problems, such as small coverage and insufficient continuity. China has the national condition of a "strong government," in which farmers' sustainable livelihoods are closely related to the government's guidance. As such, the government should establish a long-term security mechanism, increase investment in rural ecocultural tourism infrastructure and service facilities, guide farmers to actively participate in rural ecocultural tourism, and create a good livelihood environment for farmers' sustainable livelihoods. The improvement of education, experience, and skills and the promotion of the overall quality of farmers are equally important aspects of optimizing farmers' livelihood and promoting sustainable development and require long-term attention through national policies. Finally, the purpose of rural revitalization is to enhance the endogenous development capacity of farmers and encourage them to improve their livelihoods through various methods to give full play to the characteristics of regional resources. The landscape environment and cultural resources owned by minority areas are the core elements of the development of ecocultural tourism. As such, they should be vigorously protected, and farmers are the carriers of these "elements" as rural areas belong to farmers. Competitive ecocultural tourism to ensure sustainable development can only be obtained by fully harnessing the enthusiasm of farmers to participate in ecocultural tourism and transforming farmers from tourism participants to inheritors of regional culture (Wu et al., 2017; Deng et al., 2020). Therefore, it is necessary to highlight the dominant position of farmers and utilize ecological cultural tourism as the carrier of inheriting and developing distinctive rural culture. Developing characteristic tourism, promoting employment of rural farmers, attracting lost populations back to rural areas, introducing new talent, and realizing rural urbanization, agricultural modernization, and farmers' employment in minority areas must also be accomplished.

Conclusion and recommendations

In this study, the types, levels, and factors influencing the responses to ecocultural tourism of 327 farming households in six ecocultural tourism villages of Xiangxi Prefecture were analyzed by constructing an indicator evaluation system. The major conclusions were as follows:

Ecocultural tourism disturbs farmers' sustainable livelihoods. As changes in farmers' sustainable livelihoods affect the development process of ecocultural tourism, the mutual feedback between tourism and farmers promotes the evolution of rural adaptation. Nine major factors that influence the sustainable livelihood response of farmers in Xiangxi Prefecture were obtained. These were economic development, infrastructure, social development, folk culture, economic ecology, social connection, natural resource, policy awareness, and ecological development factors. These factors respond to industrial, talent, organizational, ecological, and cultural revitalization in China's rural revitalization strategy.

While the development of ecocultural tourism has enriched the diversity of farmers' sustainable livelihoods, significant differences between different livelihood response types remain. Six types of responses to sustainable livelihood were identified among farmers in Xiangxi Prefecture. In descending order, they were a developmental delay, resource advantage, ecology-dominant, balanced development, complete response, and cultural network types. The overall level of response of the farmers was generally no response. The reason for this was that the development of ecocultural tourism in Xiangxi Prefecture was not spatially balanced. Factors such as natural resources, social development, and the local economy have affected farmers' sustainable livelihood response.

Under the disturbance of ecocultural tourism, farmers' sustainable livelihoods have undergone a dynamic transformation in the form of a "steady state–unbalanced–steady state," thus promoting the sustainable development of their livelihoods. The order of different types of response levels, from high to low, was: complete response, balanced development, cultural network, ecology-dominant, developmental delay, and resource advantage. Farmers with a complete response type had the strongest response in the financial capital category, whereas farmers with an ecology-dominant response type responded most strongly in the material capital category. For other types, the strongest response was in cultural capital. The weakest response of farmers with a balanced development, ecology-dominant, or cultural network response type was in the workforce capital category, whereas that of farmers with a resource advantage or developmental delay response type was financial capital. For the complete response type, the weakest response was in social capital. These results demonstrated that farmers with a balanced development, complete response, or cultural network response type could respond more suitably to rural ecocultural tourism.

The backflow and incorporation of talent in farmers' ecocultural tourism in Xiangxi Prefecture ensured the implementation of the rural revitalization strategy. Five factors influencing farmers' sustainable livelihood response was identified. In order of degree of response, from high to low, these factors were the number of family members participating in tourism, investment in rural tourism, number of relatives and friends, family members participating in social affairs, and ethnic buildings. The willingness and behavior of farmers to participate in rural ecocultural tourism have an important impact on tourism development, and the revitalization of talents in rural revitalization is particularly urgent.

Based on the research results of the article, the paper put forward suggestions to promote the livelihood improvement of ecotourism farmers in ethnic areas, with the aim of providing effective guidance for poverty reduction and sustainable rural development in China and worldwide. Rural tourism involves multiple stakeholders and requires the concerted efforts of the government, tourism enterprises, and farmers. First, the government is the most solid backing mechanism for the people. As such, it should fully recognize the significance of ecocultural tourism for sustainable development and provide maximum rural policy support (such as land policy, talent policy, rent reduction, skills training, *etc.*) and financial support (including infrastructure construction, tourism facilities construction, *etc.*). The government should also strengthen the environmental and cultural awareness of farmers and promote ecological protection and cultural heritage. Secondly, tourism companies should consider long-term interests, give full play to the human resource advantages of farmers, and provide more jobs for farmers. They should also improve the interest relationship between farmers and tourism through capital investment, ticket dividends, and other methods to attract the active participation of farmers in rural tourism. Finally, farmers must fully seize the opportunity of tourism development, actively accept novel ideas, and improve their comprehensive ability to transform their livelihoods. As cultural skills are the most attractive resources that farmers have, they should actively innovate cultural forms, further enhance the core competitiveness of national culture, and turn intangible cultural resources into tangible cultural capital to achieve livelihood improvement.

We acknowledge that our study has several limitations. Since farmers' sustainable livelihood are a dynamic process, with the implementation of policies and changes in the social environment, farmers' sustainable livelihood adaptation and livelihood transition will face new challenges that will have increasingly complex effects on farmers' sustainable livelihood responses. This paper evaluates and analyzes farmers' sustainable livelihood responses by selecting cross-sectional data, which is not sufficient to comprehensively describe the characteristics and mechanisms of farmers' sustainable livelihood responses in ethnic tourism in a dynamic time series. In subsequent research, scholars should conduct long-term follow-ups and further explore the dynamic evolution process and mechanisms of farmers' sustainable livelihood responses through comparative analysis in different periods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization, JW; Methodology, JW; Software, LL; Validation, JZ; Formal analysis, JW; Investigation, JZ; Resources, SL; Data curation, JZ; Writing—original draft preparation, JW; Writing—review and editing, JW; Visualization, WX; Supervision, SL. All authors have read and agreed to the published version of the manuscript.

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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.

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The nature of corporate social responsibility disclosure and investment efficiency: Evidence from China

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Corporate social responsibility (CSR) disclosure has gained more attention from both practitioners and scholars. Company executives are starting to seek competitive differentiation from their sustainability strategies (McKinsey & Company, 2020). This study explores the link between CSR disclosure and investment efficiency using a sample of Chinese-listed firms from 2010 to 2019. The findings suggest that CSR disclosure improves investment efficiency through reducing information asymmetry and agency cost. Also, mandatory CSR disclosure has a more significant effect on investment efficiency than voluntary CSR disclosure. In addition, this study finds that the nature of ownership (state-owned vs. non-state-owned), CSR performance, institutional ownership, and the level of industry competition all affect this relationship. The study provides meaningful implications for future CSR disclosure policy development.

KEYWORDS

corporate social responsibility, investment efficiency, information asymmetry, agency problems, mandatory disclosure VS. voluntary disclosure

1 Introduction

Growing global concern about economic and environmental sustainability has sparked a trend toward requiring companies to disclose their corporate social responsibility (CSR) activities. Companies start to benefit from moving CSR from the sidelines into mainstream value creation. And CSR related investment strategies increased approximately 150% in 2019 according to the 2021 CSR white paper.

CSR disclosure may be defined as information that a firm makes public, typically within a stand-alone report, that relates to its performance, standards, or activities under the CSR umbrella (Brooks and Oikonomou, 2018). CSR disclosure may be mandatory—firms are legally required to deliver CSR information—or voluntary, where the extent of reporting may vary substantially among firms. CSR disclosure guidelines issued by different countries show considerable variance regarding information required to be disclosed in CSR reports (Brooks and Oikonomou, 2018). The China Securities Regulatory Commission (CSRC) began mandating certain firms to issue stand-alone CSR reports in response to emerging environmental and social issues while encouraging other firms to publish CSR reports voluntarily at the same time (Brooks and Oikonomou, 2018; Makosa et al., 2020; Liu and Tian, 2021; Zhang, 2022). For example, the Shanghai Stock Exchange announced on 30 December 2008 that firms listed in the "Corporate Governance Sector", firms with shares listed overseas, and firms in the financial industry were henceforth required to issue a CSR report with their annual report beginning with the 2008 report. The Shenzhen Stock Exchange released a similar announcement pertaining to all firms on its "Shenzhen 100 Index".

From 2001 to 2019, the number of firms disclosing CSR reports increased dramatically (for both mandatory and voluntary disclosures).

The economic consequences of CSR disclosure have aroused much attention in academia in recent years (Krüger, 2015; Chen et al., 2018; Pham and Tran, 2020; Bae et al., 2021; Qin and Yang, 2022). Many scholars have investigated the role of CSR disclosure in decreasing profitability (Chen et al., 2018), lowering financing costs (Ni and Zhang, 2019), adding value to firms (Xu et al., 2020), improving consumer loyalty (Contini et al., 2020), improving firm performance (Pham and Tran, 2020), curtailing excessive payouts (Liu and Tian, 2021), and lowering the idiosyncratic risk (He et al., 2022).

More importantly, previous research has shown that a company's CSR disclosure impacts its investment behavior. However, previous studies in this field all contain various imperfections. For example, Liu and Tian (2021), Makosa et al. (2020) study the impact of CSR disclosure on investment efficiency, but their sample is limited to the year 2008 and could not reflect the long-term effects of the policy changes. Cao et al. (2012) use Rankins CSR ratings (RKS) as a proxy for CSR disclosure quality and analyze the relationship between CSR disclosure and investment efficiency. It is worth noting that RKS only covers listed firms that publish CSR reports. In other words, their study is limited to all listed firms who disclosed CSR information but does not show the difference between disclosed and undisclosed firms. The most relevant study is Zhong and Gao (2017), which studies whether Chinese firms that issue CSR reports exhibit a higher level of investment efficiency than firms that do not issue CSR reports. However, Zhong and Gao's study mainly focuses on the role of CSR disclosure in reducing information asymmetry, neglecting other potential mechanisms.

The study makes the following contributions. First, the study differs from previous studies in that it focuses on the long-term economic benefits generated by CSR disclosure rather than the short-term impact of the mandatory CSR disclosure policy implemented in December of 2008. The empirical findings in this study provide new insights to the long-term impact of CSR disclosure on economic implications using ten-year data from 2010 to 2019. This research shows that CSR disclosure has a favorable influence on investment efficiency by reducing underinvestment, not overinvestment.

Also, this article investigates the different effects of *mandatory vs. voluntary* CSR disclosure on investment efficiency. Previous studies show voluntary CSR disclosure increases firm investment (Bouquet and Deutsch, 2008; Tan et al., 2020), but do not shed light on its effect on investment efficiency. Makosa et al. (2020) find mandatory CSR disclosure decreases firm investment but enhances investment efficiency using difference-in-difference design around 2008 when China mandated certain firms to disclose CSR information. This paper analyzes the different effects of mandatory versus voluntary CSR disclosure on investment efficiency in China using a longer sample period.

Second, this study complements and extends previous research by demonstrating that CSR disclosure improves investment efficiency, and more importantly, by investigating the underlying mechanisms. Accounting studies show that a decrease in information asymmetry and agency cost could increase investment efficiency (Jensen, 1986; Biddle and Hilary, 2006; Chen F. et al., 2011). This article adds to this line of research by providing direct empirical evidence that CSR disclosure improves investment efficiency by reducing both information asymmetry and agency cost.

Third, this paper examines the effects of CSR disclosure on investment efficiency across multiple dimensions and explores related policy implications. The study analyzes the impact of state ownership, CSR performance, institutional ownership, and industry competition on the relationship between CSR disclosure and investment efficiency. With such multi-dimensional analysis, this study tries to explain why companies' CSR disclosure could benefit their corporate governance. The findings help enhance companies' understanding of the two-fold mechanisms and encourage companies to implement CSR disclosure strategies to improve their long-term business performance. At the same time, the discussion of the economic consequences of mandatory vs voluntary CSR disclosure will also help policymakers develop and promote the implementation of CSR disclosure related policies.

In summary, many studies use the DID model to investigate the positive governance effects of CSR disclosure on corporate investment efficiency, but the specific mechanisms by which CSR disclosure affects investment efficiency remain unknown. Also, most CSR studies focus on the impact of policy shocks in 2008, ignoring the long-term effects of CSR disclosure on companies. Very little research has been conducted on the impact of mandatory vs. voluntary CSR disclosure on investment efficiency. In China's long-standing, fast-growing economy, the impact of different industry contexts and companies' characters on CSR disclosure has not been sufficiently researched and explored. The study intends to complement and extend the line of literature from above mentioned aspects.

The rest of the paper is organized as follows. Section 2 reviews related literature. Section 3 presents the development of the hypotheses. Section 4 describes the data, variables definition, and empirical models. Section 5 presents the empirical results and Section 6 is the robustness check. Section 7 reports the additional analysis and Section 8 presents the main conclusions of the paper.

2 Literature review

CSR disclosure has been shown to affect various firms' economic outcomes, such as decreasing profitability (Chen et al., 2018), lowering financing costs (Ni and Zhang, 2019), improving consumer loyalty (Contini et al., 2020), improving firm performance (Pham and Tran, 2020), adding value to firms (Xu et al., 2020), curtailing excessive payouts (Liu and Tian, 2021), promoting long-term growth and substantial innovation (Zhang, 2022), and lowering the idiosyncratic risk (Wang et al., 2018; He et al., 2022), *etc.* These studies all demonstrate the important roles CSR disclosure plays in corporate governance and keep inspiring more related studies.

A key question in corporate finance is: What motivates a firm's investment? In an ideal world, a firm's investment efficiency should be determined only by its investment opportunities (Stein, 2003; Cheng et al., 2014). Numerous studies have conclusively established that information asymmetry and agency issues impact the efficiency of business investment (Biddle et al., 2009; Chen F. et al., 2011; Shahzad et al., 2018; Wu et al., 2022). But only a few studies shed light on the relationship between CSR disclosure and investment efficiency. Cao et al. (2012) uses Rankins ESG Ratings from RKS to proxy for CSR disclosure quality and studies its impact on investment efficiency with a sample of listed companies in China. The problem with their study is that it only covers listed firms who publish CSR reports and does not differentiate between mandatory and voluntary disclosures. Zhong

and Gao (2017) also use RKS's ranking as a proxy for CSR disclosure quality and analyze its influence on investment efficiency. But their study mainly focuses on CSR disclosure's role in reducing information asymmetry and ignores the role CSR disclosure plays in reducing agency cost. Liu and Tian (2021), Makosa et al. (2020) and Zhang (2022) all study the impact of CSR disclosure on investment efficiency, but they only focus on the milestone year 2008 when China mandates CSR disclosure among certain companies. These studies do not examine the long-term effect of the CSR disclosure mandate or consider the more recent changes. The aim of this study is to complement and extend this line of research by examining the impact of CSR disclosure on investment efficiency within a longer time period and analyze the two-fold underlying mechanisms: information asymmetry and the agency problem.

Jensen and Meckling (1976) and Myers and Majluf (1984) propose a paradigm to explain the role of information asymmetry in investment decisions, which includes adverse selection and moral hazard. According to Mikkelson and Partch (1986), non-public information from management may cause investors to conclude that the capital market is overvalued, raising firms' cost of capital, and excluding otherwise suitable investment prospects. On the other hand, companies with high-quality financial information have fewer opportunities to depart from optimal investment levels (Biddle et al., 2009; Chen S. et al., 2011; Gomariz and Ballesta, 2014). By releasing environmental and other certain internal information, CSR disclosure should act as a bridge between stakeholders and company management, mitigating information asymmetry. As a result, CSR disclosure should enable managers to make more informed investment decisions and facilitates more efficient resource allocation.

Agency problems arise when managers or controlling shareholders use corporate resources for personal benefit at the expense of minority shareholders (Jensen and Meckling, 1976; Denis et al., 1997; Djankov et al., 2008). It has been argued that agency conflicts between management and shareholders, as well as between controlling and minority shareholders, significantly impact the company's investment decisions (Jensen, 1986; Fazzari et al., 1988; Jiang et al., 2010; Luo et al., 2015). Since investments are cash-flow sensitive and thus often suffer from agency problems (Pawlina and Renneboog, 2005), companies with more severe agency problems tend to spend the free cash flow on negative net present value projects rather than distribute dividends to shareholders (Jiang et al., 2010; Andrén and Jankensgård, 2015; Luo et al., 2015). For example, if stakeholders are not aware of the financial and non-financial information of the company, there would be a lack of effective communication between shareholders and managers and thus a lack of effective monitoring of managers' behavior. In such cases, management, driven by their self-interest, tends to manipulate information, such as mislead investors by reducing the readability of reports (Lo et al., 2017), make investment decisions which benefit their personal interest rather than shareholders' interest, and finally result in firms' inefficient investment (Jensen and Meckling, 1976).

The empirical evidence in this area seems to be mixed. Using a sample of US firms, Lopatta et al. (2016) discover that better corporate CSR performance reduces insider trading, mitigates information asymmetry, and mitigates agency problems. But they focus on firm CSR performance rather than CSR disclosure. Lu et al. (2017) study the effect of CSR reports on the value of cash holding and find that the voluntary issuance of a standalone CSR report substantially increases the value of cash holdings by providing incremental information. Their findings suggest that CSR disclosure reduces information asymmetry related to managerial investment decisions, which may reduce managers' opportunistic behavior when investing in excess cash holdings. On the contrary, Guo et al. (2022) find that stock price informativeness decreases after China's 2008 CSR disclosure mandate and information asymmetry between investors and managers increased significantly. They also point out that the reduction applies mainly to firms under a mandatory CSR program rather than firms that voluntarily disclosed CSR before 2008. The mixed evidence calls for more empirical studies in this field.

More importantly, existing studies do not compare the different impact of mandatory CSR disclosure versus voluntary CSR disclosure on investment efficiency. This addresses the importance of this study which intends to fill this vacuum in the literature. Previous studies on mandatory CSR disclosure have only examined its economic consequences using a natural or quasi-natural experiment and the DID model around 2008. For example, Liu and Tian (2021) find that firms subject to the mandatory CSR regulation have lower investment inefficiency using a natural experiment. Zhang (2022) discovers that mandatory CSR disclosure increases corporate innovation using quasi-natural experimentation.

On the other hand, studies show voluntary CSR disclosure also has significant economic consequences but might suffer from credibility concerns. For example, Cho et al. (2013) argue that voluntary CSR disclosure mitigates the impact of poor environmental performance on firms' reputation, but stakeholders must use filters to assess the credibility of voluntarily disclosed CSR information. Sethi et al. (2017) find that voluntary CSR disclosure has made it challenging to implement robust measures to evaluate the quality and accuracy of the reports. Nekhili et al. (2017) point out that the voluntary nature of CSR disclosure has resulted in several irregularities in reporting formats which largely affect the information value added by voluntary CSR disclosure. These studies further show the importance of research into the economic consequences of voluntary disclosure. This study analyzes how mandatory and voluntary CSR disclosure affect information asymmetry separately and differently during a ten-year period after the milestone year 2008 when China mandated certain companies to disclose CSR information.

3 Hypotheses development

3.1 CSR disclosure and investment efficiency

The goal of an enterprise is to create value and to pursue all projects with positive net present value (Luo et al., 2015). An enterprise must make investments to maximize value until its income and expenditure reaches an equilibrium (Harjoto and Jo, 2011). The volatility of the capital market as well as other pitfalls may prevent managers from accepting all profitable projects, resulting in deviations from an optimal investment level. As a result, firms with more severe capital constraints may suffer from more severe investment inefficiencies (Hubbard, 1990; Campello et al., 2010). Since managers are better informed than external investors, they are more incentivized to issue capital when companies are overvalued. Rational investors who can anticipate such managerial behavior tend to retain their capital or raise interest rates they charge, resulting in firms' higher financial constraints and underinvestment

(Stiglitz and Weiss, 1981; Biddle et al., 2009). CSR disclosure often contains vital important information and could mitigate firms' financial constraints and improve corporate investment efficiency by reducing information asymmetries. Dhaliwal et al. (2011) find that companies which initiate voluntary CSR disclosure not only benefit from a lower cost of equity capital but also appear more appealing to private investment firms and financial analysts. Similarly, Nandy and Lodh (2012) reveal that eco-friendly firms with higher environmental CSR disclosure scores can obtain more favorable and suitable loan deals than their non-eco-friendly counterparts. Furthermore, Samet and Jarboui, (2017) provide confirmatory evidence of CSR disclosure's positive impact on firm investment efficiency.

According to Freeman (1984) stakeholder theory, employees, consumers, suppliers, and investors who control resources, can affect the implementation of corporate decisions. Paying attention to stakeholders' concerns and expectations could help firms prevent stakeholders from undermining or thwarting firm's goals (Wang et al., 2016). CSR disclosure can be viewed as a response of management to shareholders' information inquiries and regulatory needs. Increasing CSR disclosure may increase the amount of information available to stakeholders and allow external stakeholders to observe and monitor firm behavior (Yusoff et al., 2013; Zhang, 2022), which further encourages companies to improve their corporate governance and investment efficiency. CSR disclosure enhances the mutual trust between managers and other stakeholders by providing more information (Cheng et al., 2014). With less short-term performance pressure, managers may pay more attention to the company's long-term interests, do more rational resource allocation, and improve investment efficiency. As a result, the first hypothesis is stated as follows.

H1: CSR disclosure improves investment efficiency.

3.2 CSR disclosure, information asymmetry, and investment efficiency

As introduced in the literature review session, information asymmetry and agency cost are the two well-established reasons behind inefficient investments. CSR disclosure could reveal information managers attempt to conceal and helps to eliminate information asymmetry (Cho et al., 2013; Lopatta et al., 2016; Cui et al., 2018). The additional information in CSR disclosure shows a more complete picture of the company's operations (Lopatta et al., 2016).

CSR disclosure could reduce the level of information asymmetry by assisting external investors to better understand the company's strategies, enhancing the efficiency of information transmission. Previous studies show that CSR disclosure could provide investors with an information edge and allows them to make better investment decisions (Cho et al., 2013), lower insider trading, and lessen information asymmetry (Lopattaet al., 2016). Capital markets are shown to be extremely sensitive to company-released CSR information, and stock markets even react directly to the positive and poor performance of CSR events (Krüger, 2015; Kölbel et al., 2017). Attig et al. (2014) show that CSR disclosure conveys critical environmental information and could potentially lower the financial cost. The most related study to ours is (Samet and Jarboui, 2017) which show the mediation function of information asymmetry between CSR activities and investment efficiency with a sample of firms listed on the Tehran Stock Exchange during 2012–2017 using content analysis. They focus on the mediating role of information efficiency in the relationship between CSR disclosure and underinvestment but not between CSR disclosure and overinvestment or the overall investment efficiency. Based on above discussion, this article states the second hypothesis as follows.

H2: Information asymmetry plays a mediating role in the relationship between CSR disclosure and overall investment efficiency.

3.3 CSR disclosure, agency cost, and investment efficiency

Agency problems have been shown to cause inefficient investment (Jensen, 1986; Biddle and Hilary, 2006). CSR disclosure could mitigate the conflicts of interest among various stakeholders and maximize shareholders' wealth (Calton and Payne, 2003; Jensen, 2010). CSR disclosure helps stakeholders perform better monitoring and governance functions, discourages opportunistic management behavior, urges managers to choose projects that are in the companies' long-term interests, and ultimately reduces inefficient investments. Harjoto and Jo (2011) find that CSR involvement reduces conflicts of interest between managers and non-investing stakeholders and increases firm value. Eccles et al. (2014) study the effect of firms' integrating social and environmental issues into corporate strategy and reveal that highly sustainable firms are more likely to have established processes for shareholders engagement, which limits short-term opportunistic behavior.

CSR disclosure could also send positive signals to market participants and enhance firm reputation, form stronger mutual trust between managers and other stakeholders within the company, and stabilize contractual relationships in the long run (Cheng et al., 2014). This enhanced stakeholder engagement will further reduce supervision costs, alleviate agency problems, and ultimately discourage inefficient investment. For example, Jo and Harjoto (2011) find that CSR is positively associated with internal and external monitoring mechanisms. CSR disclosure brings rising risks to managers by strengthening external supervision and monitoring mechanisms and impedes managers from making investments out of self-interest (Lu et al., 2017). Samet and Jarboui, (2017) also study the mediating role of agency problems in the relationship between CSR disclosure and investment efficiency, but again their study is limited to overinvestment, rather than overall investment efficiency. And their sample is from the Tehran Stock Exchange while ours is from the Chinese stock exchanges. This study proposes the following hypothesis.

H3: Reduced agency problems play a mediating role in the relationship between CSR disclosure and investment efficiency.

3.4 Mandatory vs. voluntary: The impact of CSR disclosure on investment efficiency

The Shenzhen Stock Exchange and the Shanghai Stock Exchange mandate certain listed firms to issue CSR reports at the end of

2008 while encouraging other listed companies to do so voluntarily. Previous studies show differences in the economic impact of mandatory and voluntary CSR disclosures (Dong and Xu, 2016; Chen et al., 2018). Voluntary CSR disclosure may differ largely in their focus and scope, which are mainly determined by firms' willingness to disclose. In contrast, mandatory disclosure is more standard about format, disclosing scope, and elements following the directive document issued by the government. As a result, mandatory and voluntary CSR disclosure should have different economic implications for investment efficiency. Corporations under the CSR disclosure mandate are subject to more stringent government control and, as a result, less likely to engage in irresponsible investment activities (Christensen et al., 2017). On the other hand, companies mandated to provide CSR reports are backed by the government's credibility and possess a more solid financial position. Accordingly, they should take less unproductive investments.

This study proposes the following hypothesis based on above discussion.

H4: Mandatory CSR disclosures are more effective in improving corporate investment than voluntary CSR disclosures.

4 Research design

4.1 Sample and data collection

Since 2009 was the first year the mandatory CSR disclosure policy became effective in China, the initial sample consists of all Chinese A-shares firms listed on the Shanghai and Shenzhen stock exchanges from 2010 to 2019 with 21,085 observations. This research obtains financial data from the China Stock Market and Accounting Research (CSMAR) database, and the CSR disclosure data from the RKS database (Rankins ESG Ratings database[1]). Then, the study cleans the sample according to the following procedures: First, this research excludes firms in the financial industry based on the CSRC classification criteria. The research also excludes ST/PT firms (ST: Special treatment[2]; PT: Particular Transfer[3]) This step leaves the research 19,702 observations. Second, the study winsorizes continuous variables at the top and bottom one percent to avoid the impact of outliers and get 18,714 observations. The final sample contains 18,431 observations with no missing dependent or control variables.

Table 1 shows the sample distribution by year and industry (please refer to Appendix 1 for the industry classification code). The sample distribution by year from 2010 to 2019 shows that CSR disclosures among Chinese listed companies increased over time, with mandated disclosure outnumbering voluntary disclosure until 2018. The sample distribution by industry shows that the manufacturing industry (Industry Code "C") dominates other industries with 11,724 observations which account for 63.61% of the whole sample. Other industries, such as retail and information transmission, software, and information technology services, also have a considerable number of observations.

4.2 Variable measures

4.2.1 Dependent variable: Investment efficiency

This article defines investment efficiency $Inv_{i,t}$ as the number of new investments made by the company divided by the total assets at the beginning of the year. New investment equals expenditure on the acquisition of fixed assets, intangible assets, and other long-term assets, plus net cash paid for the acquisition of subsidiaries and other business units, minus net cash recovered from the disposal of fixed assets, intangible assets, and other long-term assets minus depreciation. *TobinQ* measures the company's growth opportunities, defined as the sum of the market value of tradable shares, the book value of non-tradable shares, and liabilities divided by total assets. *Lev* is the gearing ratio. *Cash* is the ratio of cash and cash equivalents to total assets. *Age* is the number of years the company has been listed. *Size* is the size of assets. *Return* is the annual return on individual shares, considering the reinvestment of cash dividends. All control variables are lagged by 1 year. The model also controls for industry and year fixed effects.

$$Inv_{i,t} = \alpha_0 + \alpha_1 Inv_{i,t-1} + \alpha_2 TobinQ_{i,t-1} + \alpha_3 Lev_{i,t-1} + \alpha_4 Cash_{i,t-1} + \alpha_5 Age_{i,t-1} + \alpha_6 Size_{i,t-1} + \alpha_7 Return_{i,t-1} + \varepsilon_{i,t} \quad (1)$$

4.2.2 Independent variable: CSR disclosure

Following prior CSR studies (e.g., Michelon et al., 2013; Zhong and Gao, 2017; Liu and Tian, 2021), the research uses the disclosure of stand-alone CSR reports in period t-1 as a dummy variable (*CSR_Disclosure*) which equals to 1 if there is disclosure and 0 otherwise.

4.2.3 Mediating variables: Information asymmetry and agency problems

Following Dechow et al. (1995) and Hu (2021), this study applies the modified Jones model to calculate firms' information asymmetry. The modified Jones model (Dechow et al., 1995; Hu, 2021) is estimated by industry and year, and then the γ estimated in Eq. 2 are substituted into Eq. 3 to calculate the discretionary accruals (*DA*). This study uses the absolute value of *DA* to get *Opaque* which measures the information asymmetry. The larger *Opaque*, the lower the information transparency and higher information asymmetry; *TA* stands for total accruals, which is equal to operating profit minus net cash flow from operating activities; *Asset* is total assets; *PPE* is the value of fixed assets at the end of the period; ΔREV is the difference between the company's operating income in the current period and the previous period; and ΔREC is the increase in accounts receivable in the current period from last period.

$$\frac{TA_{i,t}}{As\ set_{i,t-1}} = \gamma_0 \frac{1}{Asset_{i,t-1}} + \gamma_1 \frac{PPE_{i,t}}{Asset_{i,t-1}} + \gamma_2 \frac{\Delta REV_{i,t} - \Delta REC_{i,t}}{Asset_{i,t-1}} + \varepsilon_{i,t} \quad (2)$$

1 RKS is a third-party rating agency of public interest and the authority for CSR in China. It was established in 2007 and independently developed the first rating system for social responsibility reports of listed companies in China. This database has been widely used in academic research.

2 Firms that received delisting risk warnings for two consecutive years of operating losses.

3 Firms with three consecutive years of losses and suspended from trading.

TABLE 1 Sample breakdown by year and industry.

Year	N	%	CSR_disclosure	Mandatory	Voluntary
2010	1,081	5.87	360	280	80
2011	1,186	6.43	411	300	111
2012	1,553	8.43	483	311	172
2013	1799	9.76	529	321	208
2014	1842	9.99	555	336	219
2015	1770	9.60	539	319	220
2016	1841	9.99	557	306	251
2017	2082	11.30	591	302	289
2018	2,383	12.93	674	303	371
2019	2,894	15.70	765	285	480
Total	18,431	100	5,464	3,063	2,401
Industry Code	**N**	**%**	**CSR_disclosure**	**Mandatory**	**Voluntary**
A	267	1.45	60	30	30
B	490	2.66	263	188	75
C	11,724	63.61	3,065	1,590	1,475
D	711	3.86	333	215	118
E	535	2.90	199	127	72
F	1,082	5.87	308	128	180
G	625	3.39	328	265	63
H	31	0.17	4	4	0
I	1,084	5.88	248	125	123
K	940	5.10	371	239	132
L	210	1.14	55	27	28
M	121	0.66	21	8	13
N	217	1.18	47	25	22
R	218	1.18	95	48	47
S	176	0.95	67	44	23
Total	18,431	100	5,464	3,063	2,401

Note: This table presents the year and industry (according to the industrial classification of China's national economy) distributions for the 18,431 industry-year observations between 2010 and 2019.

$$DA_{i,t} = \frac{TA_{i,t}}{Asset_{i,t-1}} - \left(\hat{\gamma}_0 \frac{1}{Asset_{i,t-1}} + \hat{\gamma}_1 \frac{PPE_{i,t}}{Asset_{i,t-1}} + \hat{\gamma}_2 \frac{\Delta REV_{i,t} - \Delta REC_{i,t}}{Asset_{i,t-1}}\right) \quad (3)$$

The study uses the difference between the actual and expected expenditures of a firm's executives to measure agency costs (Luo et al., 2011). The larger the difference, the more severe the agency problem. This is measured by the abnormal executive on-the-job consumption, expressed as the difference between management on-the-job consumption and the expected normal on-the-job consumption of executives as determined by economic factors (Luo et al., 2011). The following model measures the expected normal level of executive on-the-job consumption:

$$\frac{Perks_{i,t}}{Asset_{i,t-1}} = \delta_0 + \theta_1 \frac{1}{Asset_{i,t-1}} + \theta_2 \frac{\Delta sale_{i,t}}{Asset_{i,t-1}} + \theta_3 \frac{PPE_{i,t}}{Asset_{i,t-1}} \theta_4 \frac{Inventory_{i,t}}{Asset_{i,t-1}} + \theta_5 LnEmployee_{i,t} + \varepsilon_{i,t} \quad (4)$$

Perks is the amount of in-service consumption of executives, which is derived from administrative expenses after deducting the remuneration of directors, officers, and supervisory board members, provision for bad debts, provision for the decline in value of inventories1, and amortization of intangible assets for the year,

TABLE 2 Definition of variables.

Variable	Definition
Ineff	The absolute value of the residuals was calculated from the regression fit of Richardson's model, with larger values indicating higher levels of inefficient investment and lower firm investment efficiency
CSR_Disclosure	Equals 1 if a company releases a CSR report in period t-1, 0 otherwise
CSR_Type	*CSR_type* = 1 if the firm does not disclose the CSR report; *CSR_type* = 2 if the disclosure is voluntary; and *CSR_type* = 3 if the disclosure is mandatory
SOE	Nature of ownership, with the value of 1 if the firm is a state-owned enterprise, 0 otherwise
Opaque	Information asymmetry. The study uses the modified Jones model to calculate the absolute value
Agcost	Agency problems. It is measured by the non-monetary income of the executives
Staff	Natural logarithm of the number of employees of a company
ROA	The ratio of net profit to the average balance of total assets
Cashflow	Net cash flow from operating activities divided by total assets
Salary	Natural logarithm of the executives' remunerations
Dual	Equals 1 if the chairman of the board of directors is also the CEO; otherwise, 0
Balance	Shares held by the second to fifth largest shareholders are divided by the shares held by the first largest shareholder
Occupy	Other receivables are divided by total assets
Board	Natural logarithm of the number of board members
Top1	The ratio of the number of shares held by the first largest shareholder to the total number of shares
Inst	The ratio of the shares held by institutional investors to all tradable shares
ListAge	Natural logarithm of the number of years after the company's being listed

which is clearly not in-service consumption; *Asset* is the total assets at the end of the previous period; *Δsale* is the change in revenue from primary business for the period; *PPE* is the net value of fixed assets such as plant, property, and equipment for the period; $Inventory_{it}$ is total inventory for the period, and *LnEmployee* is the natural logarithm of the total number of employees in the business. The predicted value of the dependent variable obtained from the model is the normal on-the-job consumption, and the difference between the actual on-the-job consumption and the normal on-the-job consumption is the abnormal on-the-job consumption, represented by the variable *Agcost*. The higher the *Agcost*, the more serious the agency problem.

4.3 Model specification

To investigate the effects of CSR disclosure on investment efficiency, this research estimates the following model:

$$Ineff_{i,t} = \beta_0 + \beta_1 CSR\_Disclosure_{i,t-1} + \sum \beta Controls_{i,t-1} + \varepsilon_{i,t} \quad (5)$$

Ineff represents investment inefficiency. The larger *Ineff*, the less efficient the investment. As explained earlier, *CSR_Disclosure* indicates whether the company discloses CSR. It takes the value of 1 if the firm publishes a stand-alone CSR report and 0 otherwise. A negative coefficient indicates a reducing effect of CSR disclosure on investment inefficiency and wise versus. *Controls* include a set of control variables as listed in Table 2. ε is an error term. The quality of corporate financial information is also affected by inefficient corporate investments, so the research uses lagged CSR disclosure and financial data to avoid contemporary endogeneity issues.

Following previous studies, the study chooses several firm characteristics associated with CSR disclosure and investment efficiency as control variables (Biddle et al., 2009; Chen S. et al., 2011; Zhong and Gao, 2017; Makosa et al., 2020; Liu and Tian, 2021). All control variables are lagged by one period.

To test hypotheses H2 and H3 with regard to the impact of the mediating variables on the relationship between CSR disclosure and firm investment efficiency, the research follows Baron and Kenny (1986), Hayes (2009), Hayes and Scharkow (2013), Wen and Ye (2014) and apply the mediated model test method for empirical testing. In the relationship between the independent variable *X* and the dependent variable *Y*, if *X* affects *Y* through the intermediate variable *M*, then *M* is said to be the mediating variable. If more than one mediating variable M_i is present at the same time, the effect is said to be the multiple mediating effect.

As the two mediating variables in this study, which measure the information asymmetry and the agency problem, have very different meanings, focusing, and calculations. There is no influence relationship or specific sequence between the two mediating variables selected in this study, so the mediating effect in this article is a parallel multiple mediating effect rather than chain mediation. The model equations and are as follows:

$$Opaque_{i,t-1} = \varphi_1 + a_1 CSR\_Disclosure_{i,t-1} + \sum \omega Controls_{i,t-1} + \varepsilon_{i,t} \quad (6)$$

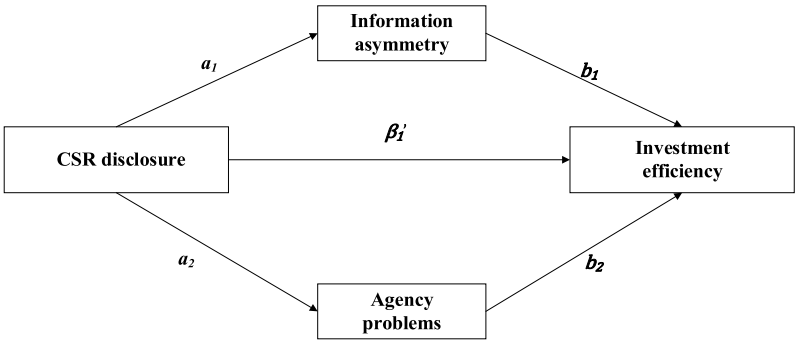

FIGURE 1
Model diagram of the multiple mediation effect.

$$Agcost_{i,t-1} = \varphi_2 + a_2 CSR\_Disclosure_{i,t-1} + \sum \lambda Controls_{i,t-1} + \varepsilon_{i,t} \quad (7)$$

$$Ineff_{i,t} = \beta_0' + \beta_1' CSR_{Disclosure_{i,t-1}} + b_1 opaque_{i,t-1} + b_2 Agcost_{i,t-1} + \sum \beta' controls_{i,t-1} + \varepsilon_{i,t'} \quad (8)$$

The approaches proceed as follows. First, the study estimates Eq. 5 and get the total effect of CSR disclosure on investment efficiency, β_1. Second, analyze the regression of *CSR_Disclosure* to *Opaque* in Eq. 6 and *Agcost* in Eq. 7 to test the significance of the regression coefficient, a_1 and a_2. Third, the coefficient b_1 and b_2 is the effect of *Opaque* and *Agcost* on *Ineff* after controlling for the effect of *CSR_Disclosure* in Eq. 8. The coefficient β_1' is the direct effect of *CSR_Disclosure* on *Ineff* after controlling for the effect of *Opaque* and *Agcost*. The model diagram is shown in Figure 1.

Please note, the indirect effect of information asymmetry (*Opaque*) and agency problems (*Agcost*) on the relationship between CSR disclosure and investment efficiency is measured by $a_i b_i$, while the direct effect of CSR disclosure on investment efficiency is equal to β_1'.

The study includes industry dummy variables to control for industry fixed effects, which may affect the relationship between firms' investment efficiency and their CSR disclosure decisions. Industry dummy variables are based on the industry code classified in Appendix 1. This research also includes dummy variables for each year in the sample period (i.e., year fixed effects) to control for changing economic conditions.

4.4 Methods

To test the hypotheses discussed here, this paper uses STATA to conduct multiple regressions to explore the impact of CSR disclosure on investment efficiency, with year and industry-fixed effects included which control for characteristics that vary over time and across industries. Given that all variables are collected at the firm level, data quality is analyzed prior to the regressions to ensure normal distribution. This study also tests the role of mediating effects.

5 Results

5.1 Descriptive statistics

Table 3 shows the descriptive statistics. The mean value of *Ineff* is 3.643%, which indicates that the average inefficient investment in the sample is 3.643%. The minimum value of *Ineff* is 0.048% and the maximum value is 26.045%, indicating that there is a relatively large difference in investment efficiency among companies in the sample. The mean value of *CSR_Disclosure* is 0.29, indicating that the percentage of companies disclosing stand-alone CSR reports in China is 29%, approximately one-third of the sample which is not high. Apart from the above variables, the means and medians of the other control variables are relatively close to each other, implying the sample is relatively balanced. *Opaque* has a mean (median) of 5.507 (3.813) and a standard deviation of 5.599, indicating a wide variation in information asymmetry among the sample companies.

5.2 Base results

In Table 4, we report the results regression models with different settings on the impact on CSR disclosure on investment efficiency based on Eq. 5. The dependent variable is investment inefficiency (*Ineff*)—the proxy for investment efficiency, and the main variable of interest is *CSR_Disclosure*. Columns (1) and (2) show GLS regression results, and columns (3) and (4) show OLS regression results. As observed in columns (1) and (3), where all control variables are excluded, we find that the coefficients on *CSR_Disclosure* are significantly negative (−0.671 with t-value = −7.702 and −0.708 with t-value = −11.527). In columns (2) and (4), when all control variables are included, the negative relationship is still existing and relatively significant (−0.206 with t-value = −2.229 and −0.239 with t-value = −3.551). The coefficients of CSR disclosure (*CSR_Disclosure*) are significantly negative which suggest that CSR disclosure significantly reduces inefficient investment. This is consistent with the hypothesis H_1.

Column (5) and (6) presents the regression results with two subsamples: Overinvestment and underinvestment. According to Richardson (2006), both overinvestment and underinvestment are

TABLE 3 Descriptive statistics.

Variables	Observations	Mean	SD	Min	Median	Max
Ineff	18,431	3.643	3.811	0.048	2.499	26.045
CSR_Disclosure	18,431	0.296	0.457	0.000	0.000	1.000
Opaque	18,431	5.507	5.599	0.000	3.813	54.931
Agcost	18,431	0.045	2.362	−12.225	−0.232	17.096
SOE	18,431	0.411	0.492	0.000	0.000	1.000
Staff	18,431	7.781	1.290	1.946	7.713	13.223
ROA	18,431	0.042	0.064	−1.859	0.037	0.675
Cashflow	18,431	0.047	0.073	−0.565	0.046	0.876
Salary	18,431	15.320	0.740	10.779	15.289	18.942
Dual	18,431	0.239	0.427	0.000	0.000	1.000
Balance	18,431	0.685	0.605	0.000	0.508	4.000
Occupy	18,431	0.016	0.029	0.000	0.008	0.726
Board	18,431	2.144	0.201	1.099	2.197	2.996
Top1	18,431	0.349	0.150	0.003	0.330	0.900
Inst	18,431	0.415	0.236	0.000	0.427	3.267
ListAge	18,431	2.280	0.653	0.693	2.398	3.401

inefficient investments although they have different economic implications. Zamir et al. (2020) find CSR disclosures reduce underinvestment for large firms but do not constrain overinvestment in emerging Asian markets. Their findings indicate the potential different impact CSR disclosure has on underinvestment and overinvestment. Thus, it is helpful to study the impact of CSR disclosure on overinvestment and underinvestment separately.

The study defines overinvestment as the positive deviations (positive residual) from the expected investment and underinvestment as the negative deviations (negative residual) from the expected investment level. The coefficient of *CSR_Disclosure* is only significantly negative (−0.207 at 1% significance level) with the underinvestment subsample which suggests that CSR disclosure only reduces underinvestment, not overinvestment.

The results of the mediating effect tests in Table 5 show that the coefficient of the total effect of *CSR_Disclosure* on firms' inefficient investment is −0.239, which passes the test at the 1% significance level. After controlling for the effects of information asymmetry and agency problems, the direct effect of CSR disclosure on investment efficiency is −0.189. According to the Bootstrap test results for mediation effects in Table 6, the indirect effect of *Opaque* is −0.021, and 95% confidence interval is (−0.028, −0.016) and does not include 0; similarly, the indirect effect of *Agcost* is −0.028, and 95% confidence interval is (−0.039, −0.017) and also does not include 0, indicating that *CSR_Disclosure* will indirectly affect investment efficiency through *Opaque* and *Agcost*. The Bootstrap test results in Table 6 also show that the total mediating effects of information asymmetry and agency cost are also significant, but the difference between the two specific mediating effects is not significant. Hypothesis H2 and H3 are verified.

Table 7 reports regression results of estimating Eq. 5 using mandatory and voluntary disclosure subsamples respectively. Since *CSR*_Disclosure is defined as a dummy variable which equals 1 if the listed company discloses a stand-alone CSR report and 0 otherwise, the coefficients of *CSR_Disclosure* in Columns (1) and (2) capture the investment inefficiency difference between disclosed group and undisclosed group within voluntary and mandatory CSR subsamples respectively. Specifically, there are 15,368 total observations in Column (1), 2,401 observations with voluntary CSR disclosure and 12,967 observations without stand-alone CSR report. There are 16,030 total observations in Column (2), 3,063 observations with mandatory CSR disclosure and 12,967 observations without stand-alone CSR report.

For example, Column (1) compares the difference in investment inefficiency between firms that made voluntary CSR disclosures and those that did not disclose stand-alone CSR reports. The coefficient of *CSR_Disclosure* is −0.164 which is insignificant statistically. This means the investment inefficiency is lower but insignificant for firms that made voluntary CSR disclosure compared to firms that did not issue stand-alone reports. Similarly, Column (2) compares the difference in investment efficiency between firms that made mandatory CSR disclosures and those that did not disclose stand-alone CSR reports. The coefficient of *CSR_Disclosure* is −0.27 which is significant at 5% significance level. This means the investment inefficiency is significantly lower for firms that made mandatory CSR disclosure compared to firms that did not issue stand-alone reports. These results indicate that mandatory CSR disclosure is more effective in improving corporate investment efficiency, which is consistent with the hypothesis H_4.

In Column (3), this article adds another discrete variable *CSR_type* which equals to 1 if the firm does not issue any CSR report; equals to 2 if the firm issues voluntary disclosure; and equals to 3 if the firm issues mandatory disclosure. The coefficient of *CSR_type* in column (3) is significantly negative, suggesting that the degree of inefficient investment decreases as *CSR_type* increases, which is also consistent with the hypothesis H4.

TABLE 4 Regression results of the impact of CSR disclosure on investment efficiency.

	(1)	(2)	(3)	(4)	(5)	(6)
	GLS	GLS	OLS	OLS	Overinvestment	Underinvestment
CSR_Disclosure	−0.671***	−0.206**	−0.708***	−0.239***	−0.165	−0.207***
	(−7.702)	(−2.229)	(−11.527)	(−3.551)	(−0.960)	(−2.608)
SOE		−0.507***		−0.516***	−0.700***	−0.376***
		(−4.830)		(−7.204)	(−3.671)	(−4.352)
Staff		−0.240***		−0.243***	−0.416***	−0.206***
		(−6.413)		(−8.891)	(−5.774)	(-6.564)
ROA		1.424***		0.367	3.630***	−0.916**
		(2.876)		(0.774)	(3.073)	(−2.100)
Cashflow		2.154***		2.977***	3.809***	1.442***
		(5.138)		(7.213)	(4.238)	(3.669)
Salary		−0.187***		−0.095**	−0.128	−0.229***
		(−3.140)		(−2.047)	(−1.104)	(−4.415)
Dual		0.143*		0.122*	0.252	−0.036
		(1.797)		(1.802)	(1.602)	(−0.497)
Balance		0.056		0.091	0.002	0.143*
		(0.652)		(1.356)	(0.014)	(1.916)
Occupy		1.375		1.702*	−0.506	2.090**
		(1.278)		(1.720)	(−0.210)	(2.192)
Board		−0.448**		−0.411***	−0.257	−0.485***
		(−2.320)		(-2.761)	(−0.682)	(−2.922)
Top1		−0.135		−0.190	0.020	−0.135
		(−0.347)		(−0.637)	(0.028)	(−0.400)
INST		0.965***		0.791***	1.324***	0.855***
		(5.658)		(5.328)	(3.699)	(5.630)
ListAge		−0.620***		−0.544***	−0.894***	−0.491***
		(−8.456)		(−9.963)	(−6.425)	(−7.905)
Constant	4.906***	11.156***	4.697***	9.677***	12.148***	10.933***
	(13.037)	(11.871)	(18.498)	(13.625)	(6.793)	(13.535)
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18,431	18,431	18,431	18,431	6,863	11,568
R^2	0.035	0.075	0.037	0.066	0.086	0.114

Note: This table reports regression results of estimating Eq. 5. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

6 Robustness check

To examine the validity of the results which indicate CSR disclosure improves investment efficiency, it runs a battery of additional tests. The study uses alternative measures of investment efficiency, alternative measures of CSR disclosure, alternative estimation methods, and several approaches to address endogeneity and self-selection bias.

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TABLE 5 Regression results from the mediating effect of information asymmetry and agency problems.

	(1)	(2)	(3)	(4)
	Ineff	Opaque	Agcost	Ineff
CSR_Disclosure	−0.239***	−0.278**	−0.431***	−0.189***
	(−3.551)	(−2.084)	(−10.196)	(−3.402)
Opaque				0.077***
				(2.914)
Agcost				0.065**
				(1.984)
SOE	−0.516***	−0.694***	0.027	−0.506***
	(−7.204)	(−6.724)	(0.607)	(−7.060)
Staff	−0.243***	−0.523***	−0.141***	−0.233***
	(−8.891)	(−13.254)	(−8.181)	(−8.456)
ROA	0.367	−5.688***	1.980***	0.414
	(0.774)	(-8.310)	(6.633)	(0.870)
Cashflow	2.977***	−11.059***	2.420***	3.095***
	(7.213)	(−18.582)	(9.323)	(7.412)
Salary	−0.095**	0.390***	0.498***	−0.110**
	(−2.047)	(5.835)	(17.096)	(−2.360)
Dual	0.122*	0.255***	0.128***	0.115*
	(1.802)	(2.613)	(3.001)	(1.709)
Balance	0.091	0.325***	−0.082*	0.088
	(1.356)	(3.350)	(−1.951)	(1.308)
Occupy	1.702*	10.171***	0.597	1.538
	(1.720)	(7.128)	(0.960)	(1.553)
Board	−0.411***	−0.762***	−0.575***	−0.389***
	(−2.761)	(−3.548)	(−6.137)	(−2.607)
Top1	−0.190	1.703***	−0.624***	−0.203
	(-0.637)	(3.971)	(-3.332)	(-0.682)
Inst	0.791***	0.194	0.220**	0.784***
	(5.328)	(0.904)	(2.359)	(5.280)
ListAge	−0.544***	0.315***	0.090***	−0.550***
	(−9.963)	(3.997)	(2.613)	(−10.077)
Constant	9.677***	6.197***	−4.925***	9.680***
	(13.625)	(6.051)	(−11.024)	(13.572)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	18,431	18,431	18,431	18,431
R^2	0.067	0.037	0.100	0.066

Note: This table reports regression results of estimating Eqs 5–8. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

TABLE 6 Bootstrap test results for mediation effects.

	Regression coefficient		95% confidence interval
Indirect effect of *Opaque*	a_1b_1	−0.021	(−0.028, −0.016)
Indirect effect of *Agcost*	a_2b_2	−0.028	(−0.039, −0.017)
Total indirect effects	$a_1b_1 + a_2b_2$	−0.049	(−0.056, −0.043)
The difference between two indirect effects	$a_1b_1 - a_2b_2$	0.007	(−0.004, 0.019)
The direct effect	β_1'	−0.189	(−0.272, −0.106)

6.1 Alternative measure of investment efficiency

This article uses Chen's model to calculate investment efficiency as a robustness test. Chen S. et al. (2011) propose the following model (Eq. 8) to calculate investment efficiency, and several scholars demonstrate that the model is equally applicable to the Chinese capital market (Dai and Kong, 2017).

$$Inv_{i,t} = \eta_0 + \eta_1 NEG_{i,t-1} + \eta_2 SalesGrowth_{i,t-1} + \eta_3 NEG_{i,t-1} \times SalesGrowth_{i,t-1} + \varepsilon_{i,t} \quad (9)$$

In the model, *Inv* represents the proportion of new investment, and its definition is consistent with Eq. 1, and *SalesGrowth* is the growth rate of operating income for the company. *NEG* is a dummy variable that takes the value of 1 if *SalesGrowth* is negative and 0 otherwise. This research also introduces an interaction term between *NEG* and *SalesGrowth* in Eq. 8. All control variables are lagged by one period. Eq. 8 is estimated by year-industry, and the absolute value of the estimated residuals are used as a proxy for investment efficiency (*Ineff _Chen*). Table 8 reports the regression results. The coefficients of *CSR_Disclosure* in column (1) are all significantly negative, with the estimates of remaining control variables consistent with the previous results.

6.2 Alternative measure of CSR disclosure

In Table 8, the study analyzes the effect of an alternative measure of CSR disclosure on investment efficiency. This research uses CSR scores from the Hexun database[4] as a proxy for CSR disclosure to test its effect on investment efficiency. The study needs to point out that compared to RKS, Hexun is more suitable for measuring the CSR performance, rather than CSR disclosure (Zhong et al., 2019). The results using the Hexun database in the research is just for robustness check purposes.

The coefficients of *CSR_Disclosure* in column (2) are significantly negative, with the estimates of remaining control variables consistent with previous results.

6.3 Alternative estimation methods

Table 8 also reports the regression results using firm fixed effects. The main results control for industry and year fixed effects. As a robustness test, the study further controls for firm fixed effects. The results remain robust. The coefficients of *CSR_Disclosure* in Table 8 are significantly negative, with the estimates of remaining control variables consistent with previous results.

6.4 Robustness check—2SLS regression

Investment efficiency might also influence CSR disclosure which causes a reverse causality problem. For example, firms with high overall investment efficiency and good financial functioning are more likely to issue CSR reports. To rule out such reverse causality from interfering with the estimation results, this study looks for exogenous instrumental variables and re-estimates the model using the 2-step least square method (2SLS). Following Song et al. (2017), this research calculates the ratio of the number of CSR disclosures over the total number of firms in the same industry-year (*CSR_rate*) as the first instrumental variable. Following Benlemlih and Bitar (2018), the study calculates the industry-year average of overall CSR scores (*CSR_Ind*) from the Hexun database as the second variable.

On one hand, *CSR_rate* and *CSR_Ind* both satisfy the relevance requirement of instrumental variables as companies in the same year and industry share similar characteristics and information environments. On the other hand, *CSR_rate* and *CSR_Ind* do not directly affect firms' investment efficiency, which also satisfies the exogeneity requirement.

Table 9 reports 2SLS regression results. Column (1) and column (3) show the results of the first stage regression using *CSR_rate* and *CSR_Ind* as instrumental variables respectively. The coefficients of both instruments are significant at the 1% significance level, which is consistent with the findings of Song et al. (2017); Benlemlih and Bitar (2018). Column (2) and column (4) show the second stage regression results using *CSR_rate* and *CSR_Ind* as instrumental variables respectively. The coefficient of *CSR_Disclosure* on inefficient investment remains significantly negative at the 1% and 5% significance level respectively, indicating *CSR_Disclosure* improves investment efficiency after considering the interference of reverse causality. These results corroborate the reliability of the main findings.

6.5 Robustness test—Propensity score matching test

The results might also be subject to self-selection bias. So, this article follows Wang and Chang (2021) and adopt propensity score

4 Hexun database was founded in 1996, standing out from the early financial and securities information services in China and establishing the first financial information vertical website. After 26 years of dedicated cultivation, Hexun.com has gradually established its dominant position and brand influence.

TABLE 7 Regression results about the mandatory vs. voluntary CSR disclosure.

	(1)	(2)	(3)
	Voluntary CSR disclosure	Mandatory CSR disclosure	Full samples
CSR_Disclosure	−0.164	−0.270**	
	(−1.453)	(−2.142)	
CSR_Type			−0.128**
			(-2.204)
SOE	−0.484***	−0.512***	−0.504***
	(−4.237)	(−4.527)	(−4.799)
Staff	−0.260***	−0.241***	−0.238***
	(−6.144)	(−6.003)	(−6.311)
ROA	1.184**	1.158**	1.432***
	(2.214)	(2.183)	(2.891)
Cashflow	2.241***	2.193***	2.153***
	(4.815)	(4.882)	(5.137)
Salary	−0.239***	−0.157**	−0.185***
	(−3.564)	(−2.457)	(−3.102)
Dual	0.114	0.103	0.144*
	(1.323)	(1.212)	(1.817)
Balance	0.030	0.016	0.054
	(0.327)	(0.174)	(0.627)
Occupy	1.625	1.522	1.377
	(1.396)	(1.337)	(1.280)
Board	−0.409*	−0.464**	−0.448**
	(-1.897)	(-2.245)	(-2.320)
Top1	−0.084	−0.339	−0.141
	(−0.198)	(−0.813)	(−0.362)
INST	0.998***	1.110***	0.969***
	(5.358)	(6.058)	(5.675)
ListAge	−0.598***	−0.638***	−0.621***
	(−7.598)	(−8.148)	(−8.477)
Constant	11.816***	10.857***	11.246***
	(11.257)	(10.806)	(12.044)
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
N	15,368	16,030	18,431
R^2	0.069	0.076	0.078

Note: This table reports regression results of estimating Eq. 5 using mandatory vs. voluntary disclosure sub-samples. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

matching (PSM) with different matching methods: k-nearest neighbor matching (k = 1, k = 2, k = 5) and radius matching (r = 0.001). The 1-1 nearest neighbor PSM matching is all with put-back sampling. As shown in Table 10, *CSR_Disclosure* remains significantly negatively related to investment efficiency under different PSM methods. The balance test results of PSM in Appendix 2.

TABLE 8 The relation between CSR disclosure and firms' investment efficiency in robustness check.

	(1)	(2)	(3)
	Ineff _Chen	Ineff	FE
CSR_Disclosure	−0.241** (−2.366)		−0.249* (−1.660)
CSR_Score		−0.007*** (−3.055)	
SOE	−0.263**	−0.520***	−0.653***
	(−2.241)	(−4.988)	(−2.805)
Staff	0.110***	−0.247***	−0.244***
	(2.675)	(−6.704)	(−3.572)
ROA	3.612***	1.883***	2.138***
	(6.936)	(3.616)	(3.781)
Cashflow	0.939**	2.179***	1.714***
	(2.112)	(5.197)	(3.721)
Salary	−0.065	−0.178***	−0.323***
	(−0.998)	(−2.977)	(−3.802)
Dual	0.261***	0.143*	0.110
	(3.066)	(1.794)	(1.053)
Balance	0.206**	0.059	−0.064
	(2.231)	(0.691)	(−0.504)
Occupy	−1.484	1.366	1.392
	(−1.314)	(1.269)	(1.104)
Board	−0.250	−0.455**	−0.571**
	(−1.188)	(−2.358)	(−1.994)
Top1	1.332***	−0.115	0.194
	(3.130)	(−0.295)	(0.307)
Inst	−0.115	0.959***	1.247***
	(−0.625)	(5.633)	(5.777)
ListAge	−0.208**	−0.632***	−1.088***
	(−2.557)	(−8.655)	(−5.229)
Constant	5.738***	11.205***	12.349***
	(5.574)	(12.049)	(8.683)
Year	Yes	Yes	Yes
Industry	Yes	Yes	No
Firm	No	No	Yes
N	18,505	18,422	18,431
R^2	0.054	0.077	0.044

Note: This table reports regression results of estimating Eq. 5 using alternative investment inefficiency measurement, alternative measure of CSR, disclosure, and alternative estimation method. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

TABLE 9 2SLS regression results.

	(1)	(2)	(3)	(4)
	Stage 1	Stage 2	Stage 1	Stage 2
CSR_rate	0.730***			
	(163.936)			
CSR_Ind			0.012***	
			(71.170)	
CSR_Disclosure		−0.355***		−0.306**
		(-3.509)		(-2.125)
SOE	0.035***	−0.495***	0.083***	−0.502***
	(6.270)	(−5.236)	(10.358)	(−5.273)
Staff	0.029***	−0.230***	0.054***	−0.234***
	(15.178)	(−6.634)	(20.323)	(−6.587)
ROA	0.059***	1.216**	0.034	1.199**
	(2.652)	(2.481)	(1.143)	(2.446)
Cashflow	−0.045**	2.323***	−0.009	2.323***
	(−2.397)	(5.556)	(-0.361)	(5.554)
Salary	0.021***	−0.153***	0.032***	−0.157***
	(7.152)	(−2.732)	(7.982)	(−2.767)
Dual	−0.008**	0.139*	−0.008	0.140*
	(−2.067)	(1.827)	(−1.504)	(1.831)
Balance	0.005	0.070	0.005	0.069
	(1.113)	(0.868)	(0.822)	(0.857)
Occupy	−0.071	1.383	−0.068	1.381
	(−1.448)	(1.309)	(−1.032)	(1.305)
Board	0.008	−0.442**	0.005	−0.442**
	(0.829)	(-2.447)	(0.408)	(-2.446)
Top1	0.024	−0.158	0.041	−0.163
	(1.245)	(−0.435)	(1.518)	(−0.450)
INST	0.043***	0.935***	0.059***	0.933***
	(5.419)	(5.662)	(5.531)	(5.631)
ListAge	0.028***	−0.586***	0.043***	−0.589***
	(7.268)	(−8.701)	(7.772)	(−8.697)
Constant	−0.608***	10.534***	−1.225***	10.624***
	(−12.818)	(12.005)	(−18.547)	(11.820)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	18,431	18,431	18,422	18,422
R^2	0.864	0.077	0.593	0.077

Note: This table reports 2SLS, regression results using *CSR_rate* and *CSR_Ind* as the instrumental variable. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

TABLE 10 Results after PSM methods.

	(1)	(2)	(3)	(4)
	1–1 match	Nearest-neighbor (k = 2)	Nearest-neighbor (k = 5)	Radius-match (r = 0.001)
CSR_Disclosure	−0.261**	−0.205**	−0.224**	−0.207**
	(−2.246)	(−1.962)	(−2.482)	(−2.221)
SOE	−0.434***	−0.501***	−0.529***	−0.499***
	(−3.007)	(−3.878)	(−4.930)	(−4.700)
Staff	−0.114**	−0.162***	−0.206***	−0.225***
	(−1.982)	(-3.236)	(-4.988)	(-5.770)
ROA	2.252**	2.961***	2.848***	1.631***
	(2.447)	(3.747)	(4.292)	(3.066)
Cashflow	3.200***	2.782***	2.325***	2.281***
	(4.419)	(4.656)	(4.633)	(5.325)
Salary	−0.144	−0.142*	−0.124*	−0.181***
	(−1.577)	(−1.807)	(−1.902)	(−2.957)
Dual	0.260*	0.175	0.168*	0.147*
	(1.936)	(1.532)	(1.815)	(1.824)
Balance	0.176	0.179	0.053	0.040
	(1.323)	(1.558)	(0.560)	(0.457)
Occupy	0.038	1.818	1.610	1.733
	(0.019)	(1.046)	(1.165)	(1.559)
Board	−0.514*	−0.677***	−0.420**	−0.462**
	(−1.734)	(−2.633)	(−1.970)	(−2.340)
Top1	0.590	0.236	−0.209	−0.158
	(1.002)	(0.463)	(-0.495)	(-0.399)
INST	0.314	0.585**	0.870***	0.960***
	(1.131)	(2.478)	(4.444)	(5.534)
ListAge	−0.695***	−0.577***	−0.589***	−0.625***
	(−6.023)	(−5.767)	(−7.195)	(−8.343)
Constant	9.499***	10.121***	9.805***	11.000***
	(6.626)	(8.114)	(9.607)	(11.455)
Year effects	Yes	Yes	Yes	Yes
Industry effects	Yes	Yes	Yes	Yes
Observations	6,082	8,873	12,743	17,870
R^2	0.080	0.083	0.084	0.072

Note: This table reports the main regression results after different PSM, methods. All variables are defined in Table 2. The research adjusts standard errors for heteroskedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

TABLE 11 The result of sub-sample test (state-owned enterprises and CSR performance).

	(1)	(2)	(3)	(4)
	SOE = 1	*SOE = 0*	*High quality CSR*	*Low quality CSR*
CSR_Disclosure	−0.320***	−0.057	−0.265**	−0.106
	(−2.933)	(−0.417)	(−2.532)	(−1.044)
SOE			−0.507***	−0.468***
			(−4.699)	(−4.304)
Staff	−0.300***	−0.219***	−0.232***	−0.259***
	(−6.435)	(−4.049)	(−5.970)	(−6.567)
ROA	−0.240	1.327**	1.287**	1.227**
	(−0.266)	(2.157)	(2.487)	(2.379)
Cashflow	1.709***	2.715***	2.233***	2.366***
	(2.972)	(4.628)	(4.986)	(5.321)
Salary	0.008	−0.303***	−0.163***	−0.186***
	(0.104)	(−3.625)	(−2.610)	(−2.959)
Dual	−0.067	0.194**	0.127	0.119
	(−0.495)	(1.970)	(1.533)	(1.433)
Balance	0.112	0.093	0.065	0.004
	(0.808)	(0.855)	(0.726)	(0.048)
Occupy	1.880	0.875	1.595	1.469
	(1.224)	(0.603)	(1.428)	(1.313)
Board	−0.295	−0.615**	−0.510**	−0.392*
	(−1.179)	(−2.294)	(−2.530)	(−1.928)
Top1	−0.463	0.220	−0.148	−0.289
	(−0.905)	(0.397)	(−0.364)	(−0.709)
INST	0.816***	1.005***	0.977***	1.021***
	(3.106)	(4.496)	(5.432)	(5.679)
ListAge	−0.634***	−0.604***	−0.597***	−0.650***
	(−5.751)	(−6.284)	(−7.972)	(−8.562)
Constant	8.710***	12.337***	10.851***	11.231***
	(6.970)	(9.489)	(11.059)	(11.376)
Year effects	Yes	Yes	Yes	Yes
Industry effects	Yes	Yes	Yes	Yes
Observations	7,567	10,864	16,409	16,428
R^2	0.119	0.043	0.082	0.076
Empirical p-value	0.050*			

Note: This table reports SOE, and non-SOE, high and low-quality of CSR, sub-sample tests. All variables are defined in Table 2. The research adjusts standard errors for heteroscedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively. The empirical *p*-value is used to test the significance of the coefficient (*CSR_Disclosure*) difference between groups, which is obtained through 1,000 times of self-sampling (Bootstrap).

7 Additional analysis

7.1 CSR disclosure and investment efficiency: Nature of ownership

State-owned enterprises (SOE) remain dominant in the Chinese capital market[5] and pressured by the State-Owned Assets Supervision and Administration Commission of the State Council (SASAC) to issue CSR reports (Zhao, 2012). SOE take more state and society-assigned responsibilities and SOE executives, who are politically motivated, are more enthusiastic to respond to CSR disclosure requirements and implement them effectively (Song et al., 2017). Consequently, compared to non-SOE, the investment behavior of SOE firms might be more influenced by CSR disclosure. In this part, this study separates firms according to their different ownership background to explore whether there is a difference in the role of CSR disclosure on investment efficiency between SOE and non-SOE.

Table 11 shows the regression results with SOEs and non-SOEs subsamples respectively. In Column (1) with the SOE subsample, the coefficient of *CSR_Disclosure* is −0.32 and significant at the 1% significance level. While In Column (2) with the non-SOE subsample, the coefficient of *CSR_Disclosure* is −0.057 and insignificant. The results suggest that CSR disclosure's role in improving investment efficiency is only significant with state-owned enterprises. This might be caused by SOEs' unique business objectives which are more social-focused than economic gains-focused. SOEs' primary business indicator is not pure profit generating, but rather the preservation of corporate assets and images. Accordingly, they are more likely to have "moral motives" for CSR disclosure. In contrast, non-SOEs' business objective is profit maximization, with CSR a mere incidental part of the business process. As a result, CSR disclosure is of limited use to non-SEOs and might contain limited information.

7.2 CSR disclosure and investment efficiency: CSR performance

Table 11 also presents the effect of CSR disclosure on investment efficiency for different CSR performance subsamples. Firms with good CSR performance are more likely to send positive signals of "good citizenship" through the publication of CSR reports ("signaling effect"). This article posits that such reports are more likely to trigger a significant impact of CSR disclosure on investment efficiency. Previous studies have found a positive impact of CSR performance on investment efficiency (Benlemlih and Bitar, 2018; Lin et al., 2021). The question naturally rises that whether CSR performance will affect the impact of CSR disclosure on investment efficiency and awaits us to answer.

Based on the CSR rating data published by RKS, this study divides the sample into two groups: high CSR performance and low CSR performance based on each industry's median score. The coefficient of *CSR_Disclosure* is −0.265 and significant at the 5% significance level for better CSR performance subsample and −0.106 and insignificant for poor CSR performance subsample. This study can conclude that CSR disclosure's effect on investment efficiency is more pronounced for companies with higher-quality CSR practices.

7.3 CSR disclosure and investment efficiency: Institutional holdings

Previous literature recognizes that stock ownership plays a vital role in limiting agency conflicts and enhancing firm value (Bathala et al., 1994). Institutional shareholding has been widely used as a proxy for external regulation. Empirical studies show that institutional holdings may influence managers' planning horizons and investment behavior (Eng and Shackell, 2001). Specifically, the higher the institutional shareholding, the stricter the external regulation and the lower the probability that firms engage in irresponsible activities (Christensen. et al., 2017). Therefore, this research investigates the impact of CSR disclosure on investment efficiency in different shareholding conditions.

This study separates the sample based on the criteria whether the institutional investors' shareholding is higher than the annual industry median. A higher than industry median institutional investors' shareholding suggests a higher level of external regulation. Table 12 reports the subsample test results. In Column (1), the coefficient of *CSR_Disclosure* for low institutional holdings subsample is −0.033 and insignificant. In Column (2), the coefficient of *CSR_Disclosure* for high institutional ownership subsample is −0.313 and significant at the 1% significance level. The results indicate that the effect of CSR disclosure on investment efficiency is more pronounced for firms with higher institutional holdings or more strict external regulation.

7.4 CSR disclosure and investment efficiency: Industry competition

Earlier studies demonstrate that industry competition determines a company's external living environment and critically influences its internal business decisions (Nickell, 1996; Karuna, 2007; Fosu, 2013; Lyu et al., 2022). When a company belongs to a more competitive industry, it usually takes a series of actions to differentiate itself from other competitors in order to be favored by investors and other stakeholders. CSR is widely considered a competitive strategy that allows companies to differentiate themselves from tier rivals (Flammer, 2015; Jia, 2020; Long et al., 2020). According to strategic management theories, implementing CSR practices and making CSR disclosure are both effective strategies companies could use to send positive signals to the market (Porter and Kramer, 2006). In other words, industry competition level is an important factor influencing firms' internal motivation for CSR disclosure.

This research predicts that industry competition strengthens the relationship between CSR disclosure and investment efficiency. The article uses Herfindahl–Hirschman Index (HHI) to measure industry competition. HHI is a commonly accepted measure of industry competition. It measures competition by squaring the market share of each firm competing in the same market and then summing the resulting numbers. The higher the HHI, the less competitive the industry is and the lower the HHI, the more competitive the industry is.

5 SOE accounted for over 60% of China's market capitalization in 2019 according to Hissey (2019) "Investing in Chinese State-Owned Enterprises".

TABLE 12 The result of sub-sample testing (institutional holdings and Herfindahl-Hirschman index).

	(1)	(2)	(3)	(4)
	Low institutional holdings	High institutional holdings	Low HHI	High HHI
CSR_Disclosure	−0.033	−0.313***	−0.288**	−0.128
	(−0.238)	(−2.706)	(−2.541)	(−0.787)
SOE	−0.384**	−0.545***	−0.438***	−0.538***
	(−2.545)	(−4.226)	(−3.421)	(−2.895)
Staff	−0.253***	−0.235***	−0.235***	−0.282***
	(−4.714)	(−4.888)	(−5.201)	(−4.032)
ROA	1.039	1.682**	0.550	2.820***
	(1.541)	(2.291)	(0.919)	(3.111)
Cashflow	2.363***	2.299***	1.942***	2.344***
	(3.988)	(3.836)	(3.866)	(3.046)
Salary	−0.264***	−0.074	−0.172**	−0.220**
	(−3.033)	(−0.959)	(−2.321)	(−2.121)
Dual	0.052	0.271**	0.042	0.317**
	(0.497)	(2.296)	(0.437)	(2.227)
Balance	0.082	0.276**	0.059	0.032
	(0.764)	(1.977)	(0.561)	(0.208)
Occupy	0.818	2.803*	0.878	1.981
	(0.525)	(1.886)	(0.664)	(1.056)
Board	−0.125	−0.735***	−0.337	−0.715**
	(−0.465)	(−2.799)	(−1.419)	(−2.114)
Top1	0.395	0.494	−0.070	−0.346
	(0.753)	(0.881)	(−0.145)	(−0.499)
INST			1.125***	0.856***
			(5.345)	(2.879)
ListAge	−0.515***	−0.567***	−0.736***	−0.415***
	(−5.265)	(−5.700)	(−8.119)	(−3.201)
Constant	11.544***	9.897***	10.520***	12.656***
	(8.556)	(7.979)	(9.112)	(7.976)
Year effects	Yes	Yes	Yes	Yes
Industry effects	Yes	Yes	Yes	Yes
Observations	9,267	9,187	12,008	6,423
R^2	0.064	0.117	0.090	0.062
Empirical p-value	0.064*	0.093*		

Note: This table reports regression results with low vs. high institutional shareholdings and low vs. high HHI., The research adjusts standard errors for heteroscedasticity. Numbers in parentheses represent t-values. ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively. The empirical *p*-value is used to test the significance of the coefficient (*CSR_Disclosure*) difference between groups, which is obtained through 1,000 times self-sampling (Bootstrap).

Table 12 report the regression results. In Column (3), the coefficient of *CSR_Disclosure* for Low HHI (high competition) subsample is −0.288 and significant at 5% significance level. While in Column (4), the coefficient of *CSR_Disclosure* for High HHI (low competition) subsample is only −0.128 and insignificant. The results indicate that the effect of CSR disclosure on investment efficiency is more pronounced among companies in highly competitive industries.

This might be explained by the stronger desire of firms from those fiercely competitive industries to gain favor and recognition from investors and shareholder. The more competitive the industry in which a company operates, the greater the pressure to survive, and the more likely the company will regulate their business practices through CSR disclosure and actively fulfill their obligations.

8 Conclusion

This study investigates the influence of CSR disclosure on investment efficiency and the underlying mechanisms. The findings suggest that CSR disclosure improves investment efficiency with a sample of Chinese listed firms. Specifically, the results show CSR disclosure has a significant impact on underinvestment, but no significant effect on overinvestment. This finding is in harmony with Benlemlih and Bitar (2018) which find that CSR has a significant effect on underinvestment, but not overinvestment. The study also shows evidence that mandatory CSR disclosure is more effective in improving corporate investment efficiency than voluntary CSR disclosure, possibly due to a lack of uniform format and content regulation for voluntary disclosure. The findings suggest that information asymmetry and agency cost act as mediating roles in this process. This study uses various tests to demonstrate the robustness of the empirical results. Furthermore, CSR disclosure by state-owned equities (SOEs) is more effective in increasing investment efficiency. And CSR disclosure by enterprises with better CSR performance, higher institutional holdings, and enterprises in more competitive industries also increases investment efficiency more effectively.

Based on the findings, the following policy recommendations are made: First, the positive impact of CSR disclosure on investment efficiency suggests that CSR disclosure could improve company reputation and increase company value as an information medium. Companies' CSR disclosure can boost market confidence and attract more potential investors, lowering financing costs, improving investment efficiency, and increasing company value. Government should continue to actively implement CSR disclosure policies through tax incentives or mandatory legislation to encourage more companies to join the ranks of disclosing CSR information. In the long run, companies would be more likely to engage in social responsibility activities and develop a steady and healthy growth.

Second, currently, not all publicly traded companies are required to publish CSR reports and there is a lack of guidance for CSR reports' formats, contents, and elements. This will hinder investors' appropriate understanding of CSR reports and increases the opportunity of managerial misbehavior. Regulators are recommended to provide more detailed guidance on the format, content, and elements of the CSR disclosure report. Furthermore, government, external institutions, consumers, and other relevant stakeholders should strengthen external monitoring to prevent firms from using CSR disclosure as a "greenwash" or "show".

This study does have several limitations which mainly stem from its failure to conduct detailed analysis of the content of CSR reports. Future research could dive into the tone, mood, content, and readability of firms' CSR disclosure using textual analysis and sentiment analysis, investigate their impact on corporate governance, and link to different stakeholder groups and audiences. Given the lack of evaluation metrics for CSR disclosure, it also calls for future studies to address the measurement and evaluation of firms' CSR disclosure quality.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

FH and MC contributed to the conceptualization and design of the study. MC wrote the original draft and contributed to analyzing it. RL contributed to the review and editing of the manuscript. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

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Appendix 1

TABLE A1 Industry classification corresponding to the industry code.

Industry code	Industry
A	Agriculture, forestry, animal husbandry, and fishery
B	Mining
C	Manufacturing
D	Electricity, heat, gas, and water production and supply
E	Construction
F	Wholesale and retail
G	Transportation, storage, and postal services
H	Accommodation and catering industry
I	Information transmission, software, and information technology services
K	Real estate industry
L	Leasing and business services
M	Scientific research and technical service industry
N	Water conservancy, environment, and public facilities management
R	Culture, sports, and entertainment
S	Public management, social security, and social organization

Appendix 2

This study used four matching measures: k-nearest neighbor matching (k = 1, k = 2, k = 5) and radius matching (r = 0.001). Before matching, the study conducted a balance test and found that the control variables between the treatment and control groups were significantly different. After matching, the standardized deviations of most variables are decreased to less than 10%. And the *t*-test is not significant. The results show that there is no significant difference in the matching variables between the two groups after the matching. The balance test results are shown in Appendix 1. Here the study only gives the balance test results for k-nearest Neighbor-match (k = 1) and Radius-match (r = 0.001). The 1-1 nearest neighbor PSM matching is all with put-back sampling.

TABLE A2 The balance test results of PSM.

Variable	Pre&Post-match	Mean		*t*-test		
		CSR_Disclosure = 1	*CSR_Disclosure* = 0	Bias%	T-value	*p*-value
SOE	Pre-match	0.609	0.327	58.80	36.760	0.000
	Neighbor-match	0.580	0.590	−2.10	−1.030	0.303
	Radius-match	0.580	0.587	−1.400	−0.690	0.492
Size	Pre-match	23.230	21.920	105.10	69.980	0.000
	Neighbor-match	23.000	23.010	−0.30	−0.150	0.881
	Radius-match	23.01	23.02	−0.300	−0.140	0.892
Dual	Pre-match	0.165	0.270	−25.60	−15.350	0.000
	Neighbor-match	0.174	0.163	2.60	1.430	0.151
	Radius-match	0.173	0.172	0.300	0.160	0.872
Lev	Pre-match	0.492	0.417	37.50	23.050	0.000
	Neighbor-match	0.482	0.486	−2.20	−1.090	0.277
	Radius-match	0.482	0.484	−0.900	−0.440	0.657
INST	Pre-match	0.517	0.372	64.80	39.900	0.000
	Neighbor-match	0.500	0.507	−3.00	−1.500	0.134
	Radius-match	0.501	0.510	−4.100	−1.970	0.0480
Top1	Pre-match	0.377	0.338	25.30	16.020	0.000
	Neighbor-match	0.369	0.372	−2.40	−1.120	0.261
	Radius-match	0.369	0.376	−4.900	−2.330	0.0200
ROA	Pre-match	0.048	0.039	13.50	8.130	0.000
	Neighbor-match	0.048	0.046	2.50	1.370	0.170
	Radius-match	0.0476	0.0482	−1	−0.520	0.602
Balance	Pre-match	0.627	0.709	−13.60	−8.380	0.000
	Neighbor-match	0.627	0.641	−2.40	−1.240	0.213
	Radius-match	0.628	0.631	−0.600	−0.300	0.762
Board	Pre-match	2.198	2.122	37.80	23.870	0.000
	Neighbor-match	2.191	2.197	−2.90	−1.400	0.163
	Radius-match	2.191	2.195	−1.800	−0.900	0.370
Indep	Pre-match	0.375	0.373	3.90	2.460	0.014
	Neighbor-match	0.373	0.373	−1.10	−0.560	0.575
	Radius-match	0.373	0.373	−0.900	−0.420	0.675

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The impact of high-tech industrial agglomeration on China's green innovation efficiency: A spatial econometric analysis

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Eco-efficiency is an important factor in assessing the quality of development, and high-tech industries are crucial for countries to forge green innovation paths. However, few studies have examined whether and how high-tech industrial agglomeration affects green innovation efficiency. To fill this gap, we measure the degree of high-tech industrial agglomeration and the level of specialized and diversified agglomeration using the location entropy index and agglomeration factor, and calculate green innovation efficiency using the super-SBM model with undesirable outputs. Based on Chinese provincial panel data from 2006 to 2020, a dynamic spatial Durbin model was constructed to explore the impact of high-tech industrial agglomeration and different agglomeration patterns on green innovation efficiency. Our study found that high-tech industrial agglomeration is a significant contributor to green innovation efficiency. There is an inverted U-shaped relationship between specialized agglomeration and green innovation efficiency, and diversified agglomeration contributes to green innovation efficiency. Given the regionally uneven nature of China's economic development, there is some variation in the impact effects within different economic regions. We demonstrated the leading role of scientific high-tech industrial agglomeration patterns and appropriate levels of agglomeration in green innovation, providing theoretical guidance for the formulation of China's high-quality development policies.

KEYWORDS

green innovation efficiency, high-tech industrial agglomeration, specialized agglomeration, diversified agglomeration, spatial econometrics

1 Introduction

After more than 40 years of rapid development, China's economic progress has generated a series of environmental problems along with considerable achievements. As China's economy shifts from high growth to a new stage of high-quality development, resource shortages, environmental constraints, and economic downturns are becoming increasingly prominent (Wu et al., 2020; Liu and Zhang, 2021). The Global Status Report on Energy and CO_2 shows that China's greenhouse gas emissions have continued to rise over the last 3 years and the country remains the world's largest emitter of greenhouse gases. In the context of China's new development path, eco-efficiency is an important factor of consideration in evaluating the quality of development (Campos et al., 2021; Qiu and Li, 2021; Wu et al., 2022). The 14th Five-Year Plan emphasizes the implementation of sustainable development strategies and promotes the comprehensive green

transformation of economic and social development (Chen and Huo, 2022; Chen and Wang, 2022; Ren and Wu, 2022). Rationalizing the relationship between economic and social development and the ecological environment and striving for stronger environmental leadership in the international stage is essential for achieving China's high-quality sustainable economic development.

As a new form of innovation that can drive rapid economic growth while avoiding negative externalities to the ecological environment, green innovation is becoming a common innovation path followed by countries around the world in the pursuit of sustainable development (Boons and Ludeke-Freund, 2013; Chen et al., 2017; Semenenko et al., 2022). Green innovation efficiency is a key indicator for measuring green innovation capabilities that not only evaluates factor utilization in the innovation process based on the traditional innovation efficiency perspective, but also introduces an undesirable output dimension, considering science and technology innovation, resource conservation, and environmental protection in an integrated manner, and presents a refinement of traditional measures of innovation efficiency (Liang et al., 2018; Luo and Zhang, 2021).

High-tech industries are knowledge- and technology-intensive, resource-saving, and environment-friendly green industries, and are an important support for countries' forging green innovation paths (Gu et al., 2020; Zhu and Li, 2021). Based on resource sharing and knowledge spillover effects, high-tech industries tend to cluster spatially, forming high-tech development zones (Wang et al., 2021; Xu D. et al., 2022). Theoretically, moderate agglomeration of high-tech industries can produce scale, knowledge spillover, and innovation interaction effects, with an impact on green innovation efficiency (Liu et al., 2022a; Wang et al., 2022). Does China's high-tech industrial agglomeration have an impact on green innovation efficiency? Does this effect show heterogeneity depending on the mode of agglomeration? These are urgent issues to be addressed in the context of high-quality development.

Based on the traditional concept of innovation, scholars have incorporated ecological elements such as resources and environmental pollution into the innovation system, introducing the concepts of green innovation, eco-innovation, environmental innovation, and sustainable innovation (Rennings, 2000; Dyck and Silvestre, 2018; Li et al., 2022), consistently emphasizing the need for innovative activities to advance sustainable development. Research on green innovation efficiency has focused on two main areas. The first is the evaluation of green innovation efficiency and analysis of its spatial and temporal evolution. Data envelopment analysis is widely used because it does not require assumptions about the relationships between variables and has obvious advantages in measuring the efficiency of decision units with multiple inputs and outputs (Chen et al., 2013; Wang et al., 2017; Garau, 2022). Evolutionary studies based on the time dimension generally have suggested that China's regional green innovation efficiency demonstrates a fluctuating upward trend (He et al., 2021; Zhang M. F. et al., 2022). From a spatial perspective, spatial differences in green innovation efficiency have been found in China, using a stepwise distribution among eastern, central, and western regions (Du et al., 2019; Shen et al., 2022). Secondly, the factors influencing green innovation efficiency were explored. Scholars have focused on the impact of environmental regulation, industrial structure, market pull, education investment, technology transfer, and foreign direct investment on green innovation efficiency (Li et al., 2018; Zeng J. Y. et al., 2021; Dong et al., 2022). Previous studies have confirmed that industrial agglomerations have innovation spillover effects (Li X. et al., 2021). Depending on the type of industry, industrial agglomerations are differentiated into specialized and diversified agglomerations, and their impact on innovation and the environment varies according to the structure of the agglomeration (Ding et al., 2022; Xu Y. et al., 2022). Industrial agglomeration patterns can only exert greater agglomeration effects and positive spatial spillovers if they are adapted to urban development conditions (Chen et al., 2008).

Academics have conducted fruitful research on green innovation efficiency, which provides a better theoretical basis and methodological insights for this paper. China's economy is at a critical stage of transition from high-rate growth to high-quality development, and high-tech industries are advancing by leaps and bounds. Unfortunately, the literature that qualitatively studies the mechanism of the role of high-tech industrial agglomeration on green innovation efficiency and empirically tests its impact effect is relatively rare, and the depth of research needs to be expanded. Scholars have mainly focused on the impact of economic phenomena generated by industrial agglomeration on green innovation, and few studies have explored the relationship between industrial agglomeration and green innovation efficiency based on the perspective of agglomeration pattern and agglomeration intensity.

In view of this, the main contribution of this paper is to integrate high-tech industrial agglomeration and green innovation efficiency into the same analytical framework. Based on the analysis of the mechanism of high-tech industrial agglomeration on green innovation efficiency, the impact paths of specialized agglomeration and diversified agglomeration on green innovation efficiency are explored. In addition, based on Chinese provincial panel data from 2006 to 2020, we construct a dynamic spatial Durbin model (SDM) to investigate the effects of high-tech industrial agglomeration and different agglomeration patterns on green innovation efficiency and regional differentiation characteristics. Our study aims to provide a scientific basis for promoting the clustering of high-tech industries in accordance with local conditions, giving full play to the clustering effect to enhance green innovation efficiency and promote high-quality regional economic development.

The rest of this article is structured as follows. The theoretical underpinnings and study hypotheses are presented in Section 2. The data and techniques are described in Section 3. The empirical findings are described and discussed in Section 4. Conclusion and policy implications are presented in Section 5.

2 Theoretical foundation and hypotheses

2.1 The effect of high-tech industrial agglomeration on green innovation efficiency

Under the premise of certain factor inputs, green innovation efficiency involves two basic elements, including the desirable

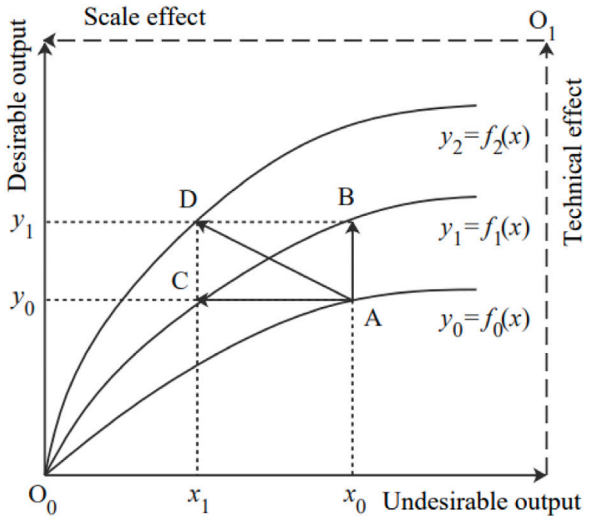

FIGURE 1
Mechanism of high-tech industry agglomeration on green innovation efficiency.

output efficiency of resource inputs and the undesirable output reduction efficiency (Song and Zhang, 2020). The scale and technology effects of high-tech industrial agglomeration are the primary factors affecting these two aspects of efficiency (Fallah et al., 2014). Desirable and undesirable outputs often arise simultaneously and together determine the efficiency of green innovation. The relationship between desirable and undesirable output is assumed to be $y = f(x)$, where y is the desirable output and x is the undesirable output. Figure 1 presents a mechanism map of the impact of high-tech industrial agglomeration on green innovation efficiency. In Figure 1, O_0 denotes the origin of desirable and undesirable output, and O_1 denotes the impact of high-tech industrial agglomeration, which can be divided into scale and technology effects. Arrows pointing to the corresponding variables increase and decrease the effects. $Y_0 = f_0(x)$, $y_1 = f_1(x)$, and $y_2 = f_2(x)$ correspond to low, medium, and high levels of green innovation efficiency, respectively. According to the law of diminishing marginal output and sustainable development theory, desirable output rises along with undesirable output, but the growth trend slows down (Lee and Johnson, 2014). The rationale for this is that a production approach that increases desirable output by expanding undesirable output is unsustainable and inevitably leads to diminishing desirable output.

In the early stages of high-tech industrial agglomeration, agglomeration is at a low level of green innovation efficiency, corresponding to the curve represented by $y_0 = f_0(x)$ in Figure 1, with a point A(x_0, y_0) on the curve. With the clustering of high-tech enterprises in a region, technology and scale effects are generated. The technology effect is a manifestation of the competitive and cooperative relationships between enterprises, wherein enterprises continuously conduct innovation activities to improve market competitiveness and internal technology levels, while leveraging knowledge spillover to achieve mutual learning and common progress, which elevates the agglomeration's overall technology level. As a result, under a certain undesirable output, the desirable output is increased (i.e., from point A to point B), and green innovation efficiency is raised from a low to a medium level. The scale effect is primarily related to enterprises' common access to public social resources in the agglomeration area, which improves efficiency in the use of public resources per unit of desirable output and reduces undesirable output, thus improving green innovation efficiency (i.e., moving from point A to point C to the left). Under combined technology and scale effects, based on the principle of vector addition, point A will move to point D [i.e., jump from curve $y_0 = f_0(x)$ to curve $y_2 = f_2(x)$], achieving green innovation efficiency.

Notably, some scholars have argued that as agglomeration grows in size, congestion effects will arise within agglomerations (Liu C. Y. et al., 2020; Zandiatashbar and Hamidi, 2021). However, we assert that high-tech industries react differently. High-tech industries are typically knowledge-intensive and technological innovation is their main feature. The rapid renewal of high-tech products constantly generates new demand, weakening the limitations of market capacity (Zuo et al., 2019). In addition, as local governments attach considerable importance to the development of high-tech industries, social resources are in sufficient supply, effectively reducing the potential congestion effect (Ostergaard and Park, 2015). Based on the theoretical analysis, we propose the first hypothesis.

Hypothesis 1: High-tech industrial agglomeration has a catalytic effect on green innovation efficiency.

2.2 The impact of different industrial agglomeration modes on green innovation efficiency

Specialized agglomeration in high-tech industries leverages the high degree of technological similarity among firms in an industry and the ease of improving the efficiency of matching firms with research and development (R&D) personnel to establish a shared market for factors, reduce the cost of learning, exchange green technology and innovation knowledge among firms, and promote green technology innovation (Mendonca, 2009). Clusters form a complete industrial chain through specialized division of labour, providing enterprises with abundant green innovation resources, which is conducive to optimizing the allocation of green innovation resources, reducing R&D and transaction costs of green innovation, and increasing economies of scale (Shuen et al., 2014). However, as the degree of specialization increases, its contribution to green innovation efficiency gradually decreases, and excessive specialization may even inhibit the improvement of green innovation efficiency. Specialized clusters can lead to increased competition among firms, and firms in a cluster tend to form a single structural pool of knowledge and labour (Li X. H. et al., 2021). This limits the innovation spillover from the agglomeration to the exchange of

information and technology within the industry, which could form a closed system with industry spatial boundaries, leading to path dependence and technology locking in the industrial structure within the agglomeration, which is not conducive to R&D and innovation activities (Zhang W. X. et al., 2022). Too much specialization can lead to traffic congestion, resource shortages, and higher production costs, inhibiting green innovation efficiency. It is possible that different degrees of specialization may have different effects on green innovation efficiency. In this regard, we propose a second hypothesis.

Hypothesis 2: There is a non-linear relationship between the specialized agglomeration of high-tech industries and green innovation efficiency.

Diversified agglomeration is an organizational model based on spatial clustering of firms with different product orientations. Unlike specialized agglomeration, the agglomeration of high-tech firms across industries makes labour market externalities more significant (Zhang et al., 2021). The clustering of workers with different professional skills in a region can create a diverse labour pool (Ozcan and Islam, 2014), and the clustering of different types of high-tech enterprises in the same area can facilitate inter-industry knowledge exchange and complementarity, and generate new knowledge, establishing a diverse knowledge pool (Pei et al., 2021). Diversified labour and knowledge pools not only avoid the homogeneity of green innovation technologies and management systems and increase firms' differentiation and innovation of green products, but also help to stimulate firms' green technological innovation (Lechner and Leyronas, 2012; Simonen et al., 2015), increasing green innovation efficiency. In addition, diversified agglomeration facilitates convenient provision of intermediate goods between firms, satisfies firms' diversified demand for inputs, and reduces transport and transaction costs, establishing the conditions for resource conservation and lower undesirable output. This leads us to our third hypothesis.

Hypothesis 3: Diversified agglomeration of high-tech industries has a catalytic effect on green innovation efficiency.

3 Model construction and variable description

3.1 Model construction

Based on theoretical analysis, we explore the impact of high-tech industrial agglomeration and different spatial agglomeration patterns on green innovation efficiency. We introduce spatial interactions into the panel regression model, combining a spatial lag model with a spatial error model to form a more general SDM (Zhao et al., 2020). Since green innovation efficiency incorporates undesirable outputs reflecting environmental pollution, which are characterized by wide reach and mobility, a one-period lag in green innovation efficiency is included in the model to reduce potential systemic bias. The SDM is constructed as follows:

$$GIE_{it} = \tau GIE_{i,t-1} + \rho WGIE_{it} + \beta_1 HIA_{it} + \beta_2 X_{it} + \theta_1 WHIA_{it} + \theta_2 WX_{it} + \mu_i + \xi_t + \varepsilon_{it} \quad (1)$$

$$GIE_{it} = \tau GIE_{i,t-1} + \rho WGIE_{it} + \beta_1 \ln SA_{it} + \beta_2 X_{it} + \theta_1 W \ln SA_{it} + \theta_2 WX_{it} + \mu_i + \xi_t + \varepsilon_{it} \quad (2)$$

$$GIE_{it} = \tau GIE_{i,t-1} + \rho WGIE_{it} + \beta_1 \ln DA_{it} + \beta_2 X_{it} + \theta_1 W \ln DA_{it} + \theta_2 WX_{it} + \mu_i + \xi_t + \varepsilon_{it} \quad (3)$$

where subscripts i and t denote province and year, respectively. W is the spatial weight matrix, GIE_{it} denotes green innovation efficiency, $GIE_{i,t-1}$ is the time lag term, and $WGIE_{it}$ is the spatial lag term. HIA_{it} denotes high-tech industrial agglomeration, SA_{it} denotes specialized agglomeration, and DA_{it} denotes diversified agglomeration. X_{it} denotes control variables. μ_i, ξ_t, and ε_{it} are spatial fixed effects, time fixed effects, and random error terms, respectively.

Spatial weight matrices that reflect the way in which geographic elements influence one another are critical to spatial measurement models (Liu and Liu, 2019). To fully consider the reality of geographic attributes, an inverse geographic distance matrix is constructed to reflect geospatial relationships between provinces. Interprovince distance data is measured using ArcGIS software's distance function, and vector-based map data is obtained from the standard map of the Ministry of Natural Resources of China (GS(2019)1719). The weight matrix uses the following formula:

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}}, & \text{if } i \neq j \\ 0, & \text{if } i = j \end{cases} \quad (4)$$

where d_{ij} denotes the distance between province i and province j. To retain the main features of the spatial weight matrix as much as possible and avoid the loss of economic interpretation of the weight matrix due to distance decay, the maximum characteristic roots of the matrix are used for normalization.

Before estimating the spatial econometric model, it is necessary to determine whether the variables are spatially dependent. We use Moran's Index (Moran's I) to perform a spatial autocorrelation test to analyze the distribution characteristics of the variables in geographic space. The formula is calculated as follows:

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \quad (5)$$

where $s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$ and $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$. x_i and x_j denote observations in provinces i and j, respectively, n is the total number of provinces, and W_{ij} is the spatial weight value between province i and province j.

3.2 Variable description and data source

3.2.1 Explained variable

We measure green innovation efficiency using a super-slacks-based measure model that includes undesirable outputs. The model expressions are as follows:

TABLE 1 Input–output indicator system of energy eco-efficiency.

Variable	Indicator	Description
Inputs	Labour (10^3 people)	R&D staff input
	Capital (10^4 Yuan)	R&D capital stock
	Energy (10^4 t SCE)	Total energy consumption
Desirable outputs	Patent (10^3 piece)	Number of green patent applications received
	Sales revenue (10^4 Yuan)	Revenue from new product sales
Undesirable outputs	Pollution index	Measured using a combination of industrial wastewater, industrial waste gas, and industrial solid waste emissions

$$\min \rho_{SE} = \frac{1 - \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{ik}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1} s_r^+ / y_{rk} + \sum_{t=1}^{s_2} s_t^{z-} / z_{tk}\right)}$$

$$s.t.$$

$$\sum_{j=1, j \neq k}^{n} x_{ij} y_j - s_i^- \leq x_{ik} \tag{6}$$

$$\sum_{j=1, j \neq k}^{n} y_{rj} y_j + s_r^+ \geq y_{rk}$$

$$\sum_{j=1, j \neq k}^{n} z_{rj} y_j + s_t^{z-} \leq z_{rk}$$

$$\gamma, s^-, s^+, s^{z-} \geq 0$$

$$i = 1, 2, \cdots, q; j = 1, 2, \cdots, n(j \neq k)$$

where ρ_{SE} is the efficiency value, x is the input variable, and y and z are the desirable and undesirable output variables, respectively. m denotes the number of input indicators; s_1 and s_2 denote the number of desirable and undesirable output indicators, respectively; k denotes the production period; and I, r, and t denote the decision units for inputs, desirable outputs, and undesirable outputs, respectively. s^-, s^+, and s^{z-} are the slack variables for inputs, desirable outputs, and undesirable outputs, respectively. γ is the weight vector. Larger ρ_{SE} values indicate higher efficiency. If $\rho_{SE} = 1$, the decision unit is efficient; if $\rho_{SE} < 1$, the decision unit is relatively inefficient (i.e., there is a loss of efficiency).

Based on the comprehensive consideration of the existing measurement indicators, data availability, and the connotation of green innovation (Li Z. et al., 2021; Zeng W. P. et al., 2021; Zhao et al., 2021), R&D personnel input, R&D capital input, and energy input are selected as input factors, the number of green patent applications and new product sales revenue are desirable outputs, and the environmental pollution index represents undesirable outputs (Table 1). Particularly, R&D capital investment is evaluated using the perpetual inventory approach and monitored using R&D capital stock. Internal expenditure on R&D capital is chosen as the initial indicator for estimation, and deflations are corrected using the R&D price index (0.45 fixed asset investment price index plus 0.55 industrial producer ex-factory price index), with 2006 as the base period (Lv et al., 2021). Energy inputs are measured using total energy consumption converted to standard coal. Green patents are based on the IPC Green List published by the World Intellectual Property Organization, and seven green technology areas are selected to reflect green innovation, including alternative energy, transportation, energy efficiency and emissions reduction, waste treatment, agroforestry, administrative regulation and design, and nuclear power generation. The environmental pollution index is obtained using the entropy method to measure industrial wastewater, industrial waste gas, and industrial solid waste emissions.

3.2.2 Explanatory variable

According to the classification criteria of the China High Technology Statistical Yearbook (2021), the high-tech industry includes six manufacturing industries, including information chemicals, medical equipment and instrumentation, pharmaceutical, electronics and communications equipment, computer and office equipment, and aerospace equipment and machinery. The degree of industrial agglomeration is measured using location entropy, Herfindahl–Hirschman, and, EG indices and other methods. In comparison, location entropy can eliminate the scale differences between regions and truly reflect industries' spatial distribution (Dong et al., 2020). We use the location entropy index to measure the level of high-tech industrial agglomeration, which is calculated using the following formula:

$$HIA = \left(e_{ir} \Big/ \sum_i e_{ir}\right) \Big/ \left(\sum_i e_{ir} \Big/ \sum_i \sum_r e_{ir}\right) \tag{7}$$

where e_{ir} denotes the number of people employed in province i's industry r.

High-tech industrial agglomeration primarily impacts green innovation efficiency through technology externalities. The main debate regarding technology externalities is whether specialized or diversified agglomeration is more conducive to knowledge and technology spillovers. Referencing Duranton and Puga (2001), the agglomeration factor is used to measure the level of specialized agglomeration (SA) and diversified agglomeration (DA) in high-tech industries. The equations are as follows:

FIGURE 2
Distribution map of provinces in China.

$$SA = \max_{j}\left(C_{ij,t}/C_{i,t}\right) \tag{8}$$

$$DA = 1\Big/\sum_{j}\left|C_{ij,t} - C_{j,t}\right| \tag{9}$$

where $C_{ij,t}$ denotes the ratio of the number of employees in industry j in the high-tech industry in province i to the number of employees in the high-tech industry in that province in period t. $C_{i,t}$ denotes the ratio of the number of employees in the high-tech industry in province i to the number of employees in the high-tech industry nationwide in period t. $C_{j,t}$ denotes the ratio of the number of employees in industry j in the high-tech industry to the number of employees in the high-tech industry nationwide in period t.

3.2.3 Control variables

Environmental regulation has positive compensating and negative offsetting effects on green innovation (Zhang et al., 2020). Environmental regulation intensity (*ER*) is measured by the amount of investment in industrial pollution control as a proportion of total industrial output. Policy support can compensate for some high R&D expenditure and risks associated with green innovation activities for firms; however, government funding may also have a crowding-out effect on firms (Liu et al., 2022b; Li et al., 2023). Government support (*GS*) is measured using the proportion of fiscal science and technology expenditure in fiscal expenditure (Liu Y. et al., 2020). The level of economic development (*ED*) provides the material basis for scientific research, technological innovation, and environmental governance and is reflected in the logarithm of the regional real GDP *per capita* for the base period 2006. Technology markets are where knowledge products are traded and are key to realizing the value of technological innovation (Kaartemo and Nystrom, 2021), and the logarithm of technology market turnover is used to reflect technology market maturity (*MM*). Foreign direct investment (FDI) is an important channel for capturing technology spillovers and the entry point for the pollution sanctuary hypothesis (Luo et al., 2021). The ratio of actual FDI to regional GDP is used to measure the level of foreign investment (*FI*).

TABLE 2 Variable descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
GIE	450	0.948	0.321	0.170	1.623
HIA	450	1.046	0.728	0.237	3.469
ln*SA*	450	0.824	0.533	0.286	2.573
ln*DA*	450	1.168	0.423	0.289	2.355
ER	450	0.153	0.090	0.037	0.521
GS	450	0.381	0.078	0.162	0.843
ED	450	2.932	2.330	0.184	26.320
MM	450	5.129	0.694	3.925	8.854
FI	450	0.187	0.598	0.069	0.588

3.2.4 Data source

Given the availability of data, we select 30 provinces in China (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2006 to 2020 as the study sample. Based on each provincial administrative region's distribution of natural resources and economic and social development, China is divided into eastern, central, and western economic regions. The distribution map of China's provinces is presented in Figure 2. Indicators that construct explained variables were obtained from the EPS data platform, China Energy Statistics Yearbook and China Environment Statistics Yearbook; indicators that construct explanatory variables were obtained from the China Science and Technology Statistical Yearbook and the China High-tech Statistical Yearbook; and the control variables were obtained from the EPS data platform and the China Urban Statistical Yearbook. Descriptive statistics for the variables are shown in Table 2.

4 Results and analysis

4.1 Evaluation of green innovation efficiency and high-tech industrial agglomeration

4.1.1 Green innovation efficiency in China

The MaxDEA 7 Ultra software is used to measure the green innovation efficiency of 30 Chinese provinces from 2006 to 2020. The results of the average green innovation efficiency based on the three major economic regions of China are presented in Figure 3.

Overall, the green innovation efficiency of the country showed a steady growth trend during the study period, and the green innovation efficiency of the economic regions had about the same growth trend as the country. In terms of different regions, due to its geographical location and first-mover advantage in economic development, the eastern region was significantly more efficient in green innovation than the central and western regions. In recent years, high-end manufacturing industries have shifted to the center, and the central economic zone has gradually become rich in human resources. With the knowledge spillover and technology diffusion effects of green innovation, the growth rate of green innovation efficiency in the central region has accelerated. The

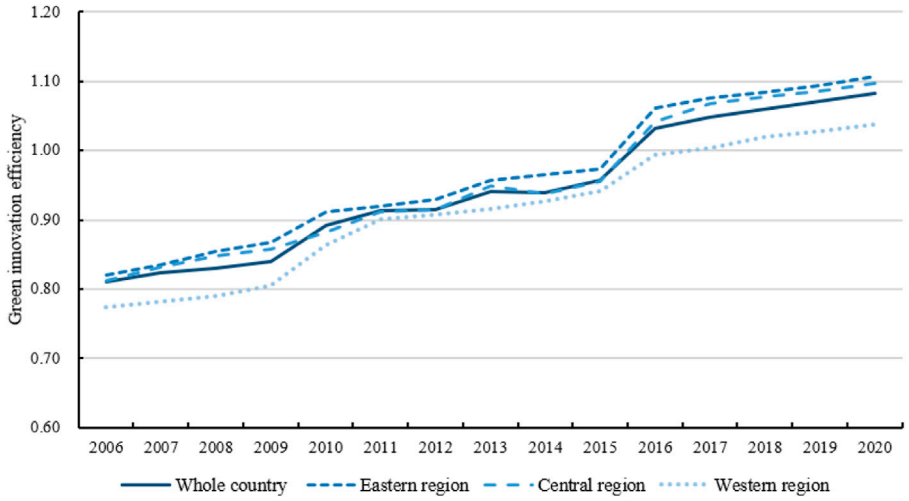

FIGURE 3
The development of green innovation efficiency.

western economic region is vast and rich in mineral resources, and the efficiency of green innovation has improved under China's Western Development strategy, but a large gap with the eastern and central regions remains. In the future, improvement in the human environment and infrastructure for green development in the west is essential, actively introducing talent, technology, and capital to facilitate the region's capability to absorb and transform the green innovation spillover from eastern and central China.

4.1.2 High-tech industrial agglomeration in China

The uneven character of China's economic development determines the regional unevenness of industrial agglomeration. Table 3 presents the level of development of high-tech industrial agglomeration and different agglomeration patterns in China. In terms of the level of development of high-tech industrial agglomeration, the degree of high-tech industrial agglomeration has increased significantly, both nationally and in the three economic regions. Industrial concentration is highest in the east, and there is a decreasing gradient distribution from the east to the centre and west. The reason is that the eastern economic region has a unique geographical location and economic policy advantages that are conducive to the rapid agglomeration and development of high-tech enterprises.

The analysis of the changes in the development of specialized agglomeration in Table 3 shows that the degree of specialized agglomeration in the national high-tech industry is steadily rising. The central economic region initially developed more slowly, but since 2010, its specialized agglomeration has been ahead of the country, even outpacing the development of the east. As the economic development of the western region has lagged behind other regions, its degree of specialized agglomeration has also lagged relatively behind. The eastern economic region is relatively developed and initially relied on policy and location advantages to absorb technology spillovers from overseas markets and promote the specialized agglomeration of high-tech industries. With the expansion of China's opening to the outside world, some high-tech enterprises have begun moving to the central and western regions of the country, leading to an increase in specialized concentration. Due to its geographical advantages and good industrial base, the specialization of high-tech industries in central China has developed rapidly.

The level of diversified agglomerations in Table 3 shows a decreasing trend from east to centre and west. As an important base for China's innovative industries, the eastern economic region is rich in talent and capital, and has a high degree of diversification in high-tech industries. On the basis of the original industries, the central region has taken over some of the high-tech enterprises transferred from the east, and the degree of diversification has increased. Overall, the degree of diversified agglomeration of China's high-tech industries shows a slow downward trend, with an evident lack of momentum in diversification.

4.2 Spatial autocorrelation test

Based on the standardized inverse geographical distance weight matrix, Moran's I is used to test the spatial autocorrelation of green innovation efficiency and high-tech industrial agglomeration (Table 4). The test results show that the variables all have significant spatial autocorrelation. The Moran's I for green innovation efficiency ranged from 0.1 to 0.3, the Moran's I for high-tech industrial agglomeration ranged from 0.2 to 0.3, and Moran's I for specialized and diversified agglomeration ranged from 0.1 to 0.2, all significant at the 5% level. This shows a significant positive spatial correlation and agglomeration characteristics between green innovation efficiency and high-tech industrial agglomeration. The reason is that agglomeration can generate intermediate product sharing, labour matching and learning effects, which facilitate enterprises to improve labour productivity and thus contribute to industrial agglomeration (Bao et al., 2023). The increase in green innovation efficiency contributes

TABLE 3 The development of high-tech industrial, specialized, and diversified agglomerations.

Variable	Region	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
HIA	Whole	0.91	0.92	0.93	0.94	0.97	0.99	1.02	1.04	1.04	1.05	1.08	1.10	1.12	1.13	1.15
	Eastern	0.92	0.93	0.95	0.97	1.01	1.02	1.03	1.06	1.07	1.08	1.12	1.17	1.18	1.19	1.21
	Central	0.91	0.93	0.94	0.96	0.98	1.00	1.01	1.04	1.03	1.05	1.09	1.12	1.13	1.15	1.17
	Western	0.87	0.88	0.89	0.90	0.93	0.95	0.98	0.99	1.00	1.00	1.04	1.03	1.05	1.06	1.08
ln*SA*	Whole	0.78	0.80	0.81	0.83	0.84	0.84	0.85	0.87	0.91	0.91	0.92	0.93	0.95	0.95	0.96
	Eastern	0.80	0.81	0.83	0.86	0.86	0.83	0.87	0.85	0.92	0.92	0.90	0.91	0.91	0.93	0.94
	Central	0.77	0.79	0.81	0.85	0.87	0.89	0.91	0.96	0.97	0.97	0.98	0.97	0.99	0.99	1.01
	Western	0.75	0.78	0.80	0.74	0.75	0.76	0.74	0.80	0.83	0.83	0.82	0.82	0.84	0.84	0.85
ln*DA*	Whole	1.21	1.17	1.15	1.14	1.13	1.12	1.14	1.14	1.12	1.11	1.09	1.07	1.08	1.07	1.06
	Eastern	1.37	1.28	1.27	1.21	1.24	1.24	1.28	1.32	1.32	1.31	1.28	1.26	1.26	1.24	1.23
	Central	1.24	1.22	1.20	1.21	1.16	1.13	1.12	1.07	1.05	1.03	1.03	1.04	1.05	1.04	1.03
	Western	1.09	1.06	1.05	1.06	1.05	1.05	1.06	1.07	1.05	1.03	1.02	0.99	0.98	0.98	0.97

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TABLE 4 Spatial autocorrelation test for variables.

Year	*GIE*	*HIA*	ln*SA*	ln*DA*
2006	0.254***	0.209***	0.146**	0.121**
2007	0.287***	0.203***	0.137**	0.124**
2008	0.232***	0.205***	0.136**	0.126**
2009	0.154***	0.217***	0.137**	0.133**
2010	0.176***	0.223***	0.143**	0.127**
2011	0.131***	0.229***	0.155***	0.136**
2012	0.134***	0.221***	0.159***	0.142**
2013	0.141***	0.230***	0.167***	0.138**
2014	0.150***	0.244***	0.180***	0.142**
2015	0.127***	0.242***	0.191***	0.152***
2016	0.128***	0.235***	0.194***	0.141**
2017	0.121***	0.239***	0.199***	0.148***
2018	0.116***	0.249***	0.194***	0.154***
2019	0.112***	0.266***	0.183***	0.159***
2020	0.122***	0.255***	0.174***	0.151***

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

to sustainable economic development and an improved innovation environment, creating an interregional virtuous circle. Therefore, it is crucial to use spatial econometric models when analyzing the impact of high-tech industrial agglomeration on green innovation efficiency.

4.3 Dynamic spatial Durbin model regression results

We establish the model as a two-way stationary dynamic SDM because of the potential for bias in the estimates due to provincial differences and inter-period factors. The Hausman test indicated that the fixed effects model was significantly better than the random effects model. LR likelihood ratio and Wald tests rejected the original hypothesis that the SDM could be reduced to a spatial lag or spatial error model at the 1% significance level. Therefore, it is reasonable to choose a dynamic SDM with two-way fixed effects. The model estimation results are presented in Table 5.

The time lag term for green innovation efficiency is significantly positive at the 1% level, indicating that green innovation efficiency has a significant time lag effect, and that accumulation of green technology and knowledge at the early stage will have a positive impact on green innovation at the later stage, indicating path dependence. The spatial lag coefficient of green innovation efficiency (ρ) is positive, passing the significance test of 1%, indicating that there is significant interregional interaction in green innovation efficiency, and the improvement of green innovation efficiency in a region will have a positive impact on green innovation efficiency in neighboring regions. This is largely due to the knowledge spillover effects of interregional cooperation and exchange.

The agglomeration of high-tech industries is conducive to green innovation efficiency. Models (1) and (2) examine the impact of high-tech industrial agglomeration on green innovation efficiency. The coefficients of the high-tech industrial agglomeration and its spatial lag term in model (1) are significantly positive at the level of 1%, indicating that an increase in the degree of high-tech industrial agglomeration positively contributes to the green innovation efficiency of a region and surrounding areas. Industrial agglomeration can reduce the transportation and learning costs of enterprises within a cluster, improve the utilization of public resources, accelerate the exchange and dissemination of green innovation knowledge and technology, and generate knowledge and technology spillover effects, thus promoting the efficiency of green innovation. At the same time, knowledge and technology spillovers from industrial agglomeration can also contribute to green innovation in neighboring regions due to the close economic and trade ties that exist between them. Model (2) introduces a quadratic term for high-tech industrial agglomeration, but it is insignificant, indicating that there is no non-linear interaction relationship. The above results confirm Hypothesis 1.

Heterogeneity exists in the impact of different industrial agglomeration patterns on green innovation efficiency. Models (3) and (4) examine the impact of specialized agglomeration on green innovation efficiency. The coefficients of the specialized agglomeration and its spatially lagged term in the model (3) are significantly negative at the 5% level. In model (4), the introduction of the quadratic term of specialized agglomeration reveals that the coefficients of the primary term of specialized agglomeration and its spatial lag term are positive and the coefficients of the quadratic term are negative, both of which are significant at the 5% level. This indicates that there is a non-linear relationship between specialized agglomeration of high-tech industries and green innovation efficiency. As the degree of specialized agglomeration increases, the efficiency of green innovation shows an inverted U-shaped curve that rises first and then falls. The reason is that while specialized agglomeration promotes green innovation efficiency through intra-industry division of labour and knowledge spillover, it tends to form a structurally homogeneous reservoir of knowledge and technology-based talent, which is not conducive to the diffusion of diversified information and technology, thus weakening the incentive for green innovation. The crowding effect of specialized agglomeration creates a scarcity of resources that can lead to unhealthy competition among firms, which inhibits the enhancement of green innovation efficiency. In addition, the region's structurally homogeneous "knowledge pool" and "labour pool," as well as the problem of resource scarcity, will inevitably continue to absorb resources and labour from neighboring regions, hindering the diversification of talent and technological innovation in the neighborhood. The above results support Hypothesis 2.

Models (5) and (6) examine the impact of diversified agglomeration on green innovation efficiency. The coefficient of the diversified agglomeration and its spatial lag term in model (5) is significantly positive at the 1% level, indicating that the diversified agglomeration of high-tech industries is conducive to enhancing the green innovation efficiency in a region and its surrounding areas. In the spatial industrial structure of diversified agglomeration of high-tech industries, differentiated enterprises among industries can generate complementary knowledge and technology spillovers,

TABLE 5 Dynamic spatial Durbin model estimation results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
L.GIE	0.547*** (0.156)	0.437*** (0.124)	0.618*** (0.183)	0.462*** (0.143)	0.551*** (0.120)	0.375*** (0.089)
HIA	0.335*** (0.081)	0.262*** (0.053)				0.2743*** (0.0452)
HIA^2		0.052 (0.063)				−0.0162 (0.0375)
ln*SA*			−0.132** (0.051)	0.122** (0.045)		
$\ln^2 SA$				−0.219*** (0.053)		
ln*DA*					0.475*** (0.098)	0.447*** (0.123)
$\ln^2 DA$						0.075 (0.101)
ER	−0.174** (0.062)	−0.163** (0.053)	−0.185** (0.063)	−0.150** (0.072)	−0.219*** (0.023)	−0.140*** (0.033)
GS	0.535*** (0.124)	0.445*** (0.136)	0.471*** (0.153)	0.464*** (0.128)	0.502*** (0.167)	0.528*** (0.119)
ED	0.276*** (0.069)	0.243*** (0.071)	0.192*** (0.055)	0.224*** (0.053)	0.194** (0.082)	0.170** (0.073)
MM	0.398*** (0.103)	0.356*** (0.094)	0.227*** (0.053)	0.268*** (0.071)	0.187*** (0.055)	0.206*** (0.64)
FI	−0.059* (0.045)	−0.057* (0.045)	−0.042 (0.064)	−0.030 (0.051)	−0.061* (0.046)	−0.058* (0.045)
ρ	0.685*** (0.192)	0.596*** (0.153)	0.692*** (0.208)	0.512*** (0.149)	0.537*** (0.154)	0.551*** (0.120)
W· HIA	0.198*** (0.040)	0.202*** (0.042)				0.2024*** (0.0423)
$W\cdot HIA^2$		−0.032 (0.045)				−0.0061 (0.0153)
W· ln*SA*			−0.108** (0.045)	0.097** (0.034)		
$W\cdot \ln^2 SA$				−0.189*** (0.051)		
W· ln*DA*					0.254*** (0.071)	0.169*** (0.043)
$W\cdot \ln^2 DA$						0.056 (0.060)
W· ER	0.034* (0.022)	0.012 (0.029)	0.027 (0.023)	0.056* (0.024)	0.010 (0.015)	0.014 (0.038)
W· GS	0.059 (0.071)	0.060 (0.071)	0.117* (0.057)	0.087 (0.095)	−0.120* (0.066)	−0.060 (0.071)
W· ED	0.145** (0.053)	0.144** (0.052)	−0.093** (0.032)	−0.193*** (0.054)	0.185*** (0.060)	0.138** (0.051)
W· MM	0.078*** (0.017)	0.070*** (0.014)	0.104*** (0.022)	0.129*** (0.027)	0.092*** (0.026)	0.079*** (0.021)
W· FI	−0.089** (0.037)	−0.091** (0.038)	−0.057 (0.062)	−0.086* (0.065)	−0.091** (0.038)	−0.041 (0.069)
Wald test spatial lag	113.238 (p = 0.000)	104.723 (p = 0.000)	90.432 (p = 0.000)	128.842 (p = 0.000)	87.632 (p = 0.000)	99.134 (p = 0.000)
Wald test spatial error	91.572 (p = 0.000)	80.756 (p = 0.000)	75.840 (p = 0.000)	102.049 (p = 0.000)	65.407 (p = 0.000)	80.394 (p = 0.000)
LR test spatial lag	76.38 (p = 0.000)	72.42 (p = 0.000)	65.95 (p = 0.000)	82.70 (p = 0.000)	77.91 (p = 0.000)	75.32 (p = 0.000)
LR test spatial error	41.26 (p = 0.000)	40.58 (p = 0.000)	37.59 (p = 0.000)	60.83 (p = 0.000)	54.65 (p = 0.000)	44.05 (p = 0.000)
R^2	0.705	0.459	0.474	0.732	0.663	0.509
N	450	450	450	450	450	450

Note: ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors are in parentheses.

establishing a driving force for technological innovation and promoting green innovation efficiency. In addition, a diversified pool of labour and knowledge is conducive to promoting the exchange of information and rational allocation of resources between industries, providing a good demonstration and driving force for neighboring regions, which in turn stimulates green technology innovation. Model (6) introduces a quadratic term for diversified agglomeration but is insignificant, indicating that there is no non-linear interaction relationship. Hypothesis 3 is confirmed.

4.4 Endogeneity and robustness tests

We use a dynamic SDM with two-way fixed effects to mitigate the endogeneity problem that may be caused by omitted variables. Given that both high-tech industrial agglomeration and green innovation efficiency are outcome variables, there is inevitably an inverse causal relationship between the two and endogeneity issues arise. Industrial agglomeration has inertial development characteristics and may have lagged effects (Schiff, 2015); therefore, the level of industrial agglomeration with a one-

TABLE 6 Results of endogeneity and robustness tests.

Variable	Endogenous treatment			Spatial weight matrix transformation			Special sample exclusion		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
HIA	0.312*** (0.078)			0.290*** (0.075)			0.376*** (0.094)		
lnSA		0.120** (0.044)			0.143*** (0.038)			0.154*** (0.043)	
ln^2SA		−0.208*** (0.051)			−0.211** (0.072)			−0.237*** (0.060)	
lnDA			0.453*** (0.117)			0.522*** (0.139)			0.499*** (0.112)
W· HIA	0.176*** (0.037)			0.203*** (0.058)			0.144** (0.057)		
W· lnSA		0.099** (0.035)			0.112** (0.041)			0.088** (0.032)	
W· ln^2SA		−0.176*** (0.048)			−0.180*** (0.051)			−0.167** (0.064)	
W· lnDA			0.260*** (0.074)			0.298*** (0.080)			0.217*** (0.055)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.663	0.694	0.621	0.686	0.713	0.645	0.720	0.741	0.697
N	450	450	450	450	450	450	390	390	390

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are in parentheses.

period lag is selected as an instrumental variable. In addition, topographic relaxation, as a naturally occurring and objective exogenous variable, will have an impact on transport and infrastructure development, and has a significant correlation with industrial agglomeration (Mori and Smith, 2015), making it an appropriate instrumental variable. We use the system-wide instantaneous method for estimation tests. The LM and Hansen J test results justify instrumental variables by passing unidentifiable and overidentifiable tests, respectively. The estimation results are presented in models (1)–(3) in Table 6.

We take two approaches to robustness testing. The first is transforming the spatial weight matrix, which is constructed using (0, 1) neighborhoods instead of inverse geographical distances, and the estimation results are presented in models (4)–(6). Second, municipalities directly under the central government are excluded. Since municipalities are directly administered by the central government, their development plans may differ from those of prefecture-level cities (Lin and Zhu, 2021); thus, central government administered municipalities are excluded to avoid policy bias and the estimation results are presented in models (7)–(9).

Table 6 reveals that the endogeneity treatment and robustness tests validate the credibility of the study's findings. Estimated coefficients of core explanatory variables did not change significantly with the introduction of instrumental variables, and the direction of influence and significance levels remained unchanged. The robustness test results show that the transformation of the spatial weight matrix and the exclusion of municipalities did not affect the relationship between the core explanatory variables and green innovation efficiency. This indicates that the model estimation results are robust and the study findings are credible.

4.5 Heterogeneity analysis

The above empirical studies mainly examine the impact of high-tech industrial agglomeration on green innovation efficiency at the national level. Due to the diversity of geographical location conditions and resource endowments in different regions of China, spatial differences are expected in both green innovation efficiency and the degree of high-tech industrial agglomeration. Therefore, we carry out grouped regressions for the eastern, central and western regions, to examine the impact of high-tech industrial agglomeration and different agglomeration patterns on green innovation efficiency from the perspective of regional heterogeneity. The estimation results of the dynamic SDM are shown in Table 7.

In terms of high-tech industrial agglomeration, the eastern, central and western economic regions contribute positively to green innovation efficiency through industrial agglomeration. The impact is stronger in the eastern region than in the central and western regions due to the relatively superior infrastructure and public services, which are conducive to the knowledge and technology spillover dividends that the high-tech industrial agglomeration can bring to green development. At the same time, the relatively developed economic and social environment of the eastern region also has a clear advantage in attracting highly skilled personnel and capital. This highlights the importance of developing policy guidelines to rationally promote the clustering and coordinated development of high-tech enterprises in each region.

Regarding specialized agglomeration, the eastern region's specialized agglomeration has a negative impact on green innovation efficiency, the specialized agglomeration in the central economic region has an inverted

TABLE 7 Results of regional heterogeneity analysis.

Variable	Eastern region			Central region			Western region		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
HIA	0.423*** (0.102)			0.357*** (0.074)			0.298*** (0.065)		
lnSA		−0.310*** (0.086)			0.143*** (0.038)			0.167*** (0.042)	
ln^2SA		0.028 (0.045)			−0.211** (0.072)			−0.037 (0.050)	
lnDA			0.245*** (0.117)			0.210*** (0.139)			0.199*** (0.112)
W· HIA	0.308*** (0.089)			0.223*** (0.054)			0.153** (0.036)		
W· lnSA		−0.197*** (0.041)			0.112** (0.041)			0.095** (0.036)	
W· ln^2SA		0.016 (0.039)			−0.180*** (0.051)			−0.028 (0.044)	
W· lnDA			0.307*** (0.088)			0.265*** (0.074)			0.204*** (0.059)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.612	0.529	0.637	0.580	0.713	0.559	0.623	0.540	0.585
N	180	180	180	135	135	135	135	135	135

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are in parentheses.

U-shaped relationship with green innovation efficiency, and the specialized agglomeration in the western economic region is conducive to improving green innovation efficiency. The reason may be that the eastern region has a developed economy and a high concentration of high-tech enterprises. Specialized agglomeration can cause problems such as traffic congestion, resource shortages, and rising production costs, which inhibit green innovation efficiency. During the study period, specialized agglomeration in the central region developed rapidly, and under the combined effect of positive and negative externalities generated by specialized agglomeration, green innovation efficiency showed an upward and then downward trend. In the western region, the degree of high-tech industrial agglomeration is low, and the crowding effect generated by specialized agglomeration is insignificant, indicating a positive agglomeration effect on green innovation efficiency.

The diversified agglomeration of high-tech industries in the eastern, central and western economic regions indicates a significant contribution to green innovation efficiency. This is consistent with the test results of national data. Diversified agglomeration forms a diverse pool of labour and knowledge, which is conducive to stimulating the technological innovation of enterprises and promoting green technological innovation. In addition, diversified agglomeration facilitates the easy provision of intermediate products between firms and reduce transport and transaction costs, thus creating conditions for saving resources and reducing undesirable output, and thus enhancing the green innovation efficiency. In the future, a balanced spatial distribution of high-tech enterprises, the coordinated development of industries across regions, and the level of diversified agglomeration in each province should be promoted.

5 Conclusion and discussion

5.1 Conclusions

Green development is a critical component of China's new era of high-quality economic development, and improving the efficiency of green innovation is essential for achieving green development. As a strategic industry for economic development, the high-tech industry has considerable advantages in reducing energy use, improving efficiency, and promoting economic structural transformation, and is an important driving force for achieving green innovation. We reveal the mechanism of the effect of high-tech industrial agglomeration on green innovation efficiency through theoretical analysis. Using a sample of 30 Chinese provinces from 2006 to 2020, we establish a dynamic SDM to empirically test the effect of high-tech industrial agglomeration on green innovation efficiency, conducting a comprehensive analysis of the impact of different agglomeration patterns.

The relevant findings are threefold. 1) China's green innovation efficiency and high-tech industrial agglomeration level exhibit a stable growth trend, and spatial distribution is roughly characterized by a gradual decrease from east to west. Specialized agglomeration is rapidly developing, while diversified agglomeration is relatively underdeveloped. 2) At the national level, high-tech industrial

agglomeration has a significant effect on green innovation efficiency, and different agglomeration patterns have heterogeneous effects. There is an inverted U-shaped relationship between specialized agglomeration and green innovation efficiency, while diversified agglomeration is conducive to promoting green innovation efficiency. 3) Regional heterogeneity in the impact of high-tech industrial agglomeration and different agglomeration patterns on green innovation efficiency is evident. The promotional effect of high-tech industrial agglomeration on green innovation efficiency is significant in all three economic regions, and the intensity of this effect is decreasing. Specialized agglomeration in the eastern economic region has a significant negative impact on green innovation efficiency, while the central economic region shows an inverted U-shaped relationship, while specialized agglomeration in the western economic region is conducive to promoting green innovation efficiency. Welcoming the results of the national test, the diversified agglomeration within the three economic regions makes an important contribution to green innovation efficiency.

5.2 Policy implications

The findings of our study provide policymakers with three practical implications for improving green innovation. First, the development of high-tech industrial agglomeration should be accelerated. In terms of macro policy formulation, emphasis should be placed on coordinated national planning, deepening structural reform on the supply side, actively nurturing and introducing high-tech enterprises, strengthening the spatial clustering of high-tech industries, and effectively releasing the potential of high-tech development regions to enhance green innovation efficiency. The government should seize the opportunities presented by the paradigm shift of the digital economy and promote digitization, intelligence and greening in high-tech industries, prioritize strategic emerging industries and green industry clusters, accelerate the upgrading and transformation of obsolete production capacity, and promote the integration of high-end and green industries (Prah, 2022).

Second, diversified agglomeration of high-tech industries should be promoted to achieve diversified development of high-tech enterprises. A large number of science and technology elements and innovation resources are gathered in high-tech industrial clusters, which should be leveraged to promote the transfer and production of green innovation knowledge and technology among enterprises by building diversified application scenarios to continuously stimulate the generation of new products, technologies and business models. The government should actively guide the regulation of competition and cooperation among high-tech enterprises to avoid large-scale homogenous clustering and the resulting crowding effects (Tsuji, 2022).

Third, policy guidelines should be developed to promote the development of high-tech industrial agglomeration in accordance with local conditions (Atta-Mensah, 2021). In view of the development status of China's three major economic zones, when guiding high-tech industrial agglomeration, industrial support policies and key development areas should be identified in relation to the specific stage they are in to effectively leverage the positive externalities of industrial agglomeration and generate the synergistic enhancement of the regional economy, innovation capacity, and ecological environment. The eastern economic region has the advantage of high-tech concentration and the development of intensive industries. The region should actively implement industrial transfer policies to transfer over-specialized labour-intensive industries to the central and western regions, promote industrial structure upgrading, and increase the level of diversified agglomeration. The central economic region should build on the sound development of existing industries and transfer into a number of coordinated and relevant industries to effectively absorb the spillover effects of knowledge and technology. Considering factors such as economic development, industrial base, and human resources, it is appropriate for the western economic region to prioritize the development of industries with regional characteristics and policy-oriented industries and actively receive a continuous inflow of capital, talent, and other resources that can be transformed into green innovation outputs.

5.3 Limitations and future directions

Although detailed theoretical analysis and empirical testing are carried out, there are still areas worth further expansion in future research. First, we recognize that the provincial panel data used have sampling limitations because they ignore regional and international variations. In emerging economies, where various resource endowments and cultural values may have an impact on the linkages between variables, high-tech industrial agglomeration is a complex issue. As data availability and statistics improve, future research should test these results at the level of other emerging countries and cities. Second, our measurement of high-tech industrial agglomeration is only considered by industry as a whole, and further research on the agglomeration effect of sub-sectors is encouraged. Finally, given the complex impact of high-tech industrial agglomeration and different agglomeration patterns on green innovation efficiency, a non-parametric spatial model could be applied in the future to analyze the non-linear interaction between them.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.epsnet.com.cn/index.html#/Index.

Author contributions

SL: writing-original draft preparation, methodology, conceptualization. PW: writing—reviewing and editing, validation, supervision. All authors have read and agreed to the published version of the manuscript.

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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.

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How urban development affects green development efficiency in China: Taking the city cluster of Yangtze river economic belt as an example

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Introduction: In order to change the long-term economic development model which is at the expense of the environment, China proposed a series of new energy development and environmental intervention policies. However, there is no evidence to support the impact of urban development on the green development efficiency (GDE) under China's macroeconomic policies at present. In order to answer this research question and help the government to improve the GDE, this study takes the Yangtze River Economic Belt (YREB) city cluster (41 cities) in China as an example to conduct an empirical study.

Methods: We first measure the GDE of these cities by Slack Based Model (SBM). Then, the Tobit model is used to measure the impact of urban development elements, namely population urbanization, land urbanization, and urban industrial development, on GDE.

Results and Discussion: The analysis of the data leads to the following conclusions and suggestions: 1) The GDE of the city cluster in the YREB has generally been improved driven by policies. But compared to policy interventions, the level of science, technology and management are the primary drivers of long-term improvement in GDE. 2) In order to avoid the economic development and environmental capacity failure to afford the increase in energy consumption and pollution discharge caused by population urbanization and land urbanization, local governments need to promote energy transformation, increase environmental protection efforts and attract top-tier talent. 3) The improvement of GDE by industrial upgrading is a dynamic and slow process, and blindly pushing industrial restructuring will lead to a decline in GDE. Therefore, the Chinese government needs to provide an ecologically suitable environment for local industrial development, which needs to avoid "pulling out the seedlings" and "one-size-fits-all" approach.

KEYWORDS

urban development, green development efficiency, SBM model, tobit model, China

1 Introduction

Many urban cities all around the world have seen rapid industrialization and quick economic growth in recent decades. However, urban development has resulted in a number of environmental and ecological issues, including water pollution, global warming, and the destruction of ecological systems (Sassen, 2010; Liu D et al., 2022; Hao, F. et al., 2020). If the environmental and ecological issues are not effectively alleviated and improved, they will, in turn, inhibit urban development (Brown, 2012). What is more, it may also contribute to a number of ancillary catastrophes, including food production decline, land pollution, and sea level rise (Vignola and Oosterveer, 2022; Jácome Polit D et al., 2022; Karimian Shamsabadi M et al., 2022). Therefore, researchers and urban governments around the world have to think more about how to alter the urban development model which is at the price of ecology and the environment to a more environment-friendly and sustainable way.

Urban economies are heavily reliant on fossil fuels like coal, oil, and natural gas. The use of these energy sources will unavoidably harm the environment and the ecosystem. Therefore, energy transition, namely, the replacement of traditional fossil fuels with green and clean energy, has been widely promoted by the United Nations Environment Programme (UNEP) (Neira, 2020). These green and clean energy sources include wind, hydro, solar, bioenergy, and geothermal energy. In this background, the concept of green development was introduced, which is a sustainable development approach that prioritizes social fairness, a low-carbon economy, and efficient energy utilization (Barbier, 2011). As early as the 1970s, some developed countries began to promote the green development of urban cities through laws and acts (Du Pisani, 2006). For instance, the Clean Air Act (1956) of the United Kingdom promoted energy transition in the traditional industry; the Basic Law for Public Health Measures (1967) of Japan clearly stipulated the basic responsibility of the state to protect national health and maintain the quality of the living environment; the Federal Pollution Control Act (1974) of German mainly set emission standards for large industrial enterprises; the National Environmental Policy Act (1969) of America proposed to maximize the benefits of using environmental resources while minimizing environmental degradation, health crisis, and safety risks. Subsequently, more and more countries have also started to make green development transformation. In January 2021, the Global Climate Summit 2021 (AS 2021) re-emphasizes the urgency of the energy transition and reduction of greenhouse gas emissions, which makes green development a global goal for contemporary urban development.

China first proposed "green development" to deal with the challenges of sustainable development in China's Sustainable Development Strategy Report (2010). Then, in the next year, the goals of green development for cities were stated in the 12th Five-Year Plan for National Economic and Social Development (2011–2015). In addition to promoting clean energy conversion and efficient energy use, China's green development emphasized more on economic growth as well as improving the environment and ecology (Hong et al., 2018; Lei, W et al., 2022). To achieve these goals, important laws, such as the Environmental Protection Law (2015), the Water Pollution Prevention and Control Law (2017), the Energy Conservation Law (2018), and the Circular Economy Promotion Law (2018), have been issued. At the same time, China has also put forward supporting policies such as the Industrial Green Development Plan (2016–2020), Green Manufacturing Project Implementation Guide (2016–2020), Guidance on Accelerating the Establishment of a Sound Green Low-Carbon Circular Development Economic System (2021). Currently, green development has become a crucial urban development strategy for China to ensure the coordinated development of the environment and economy (Zeng and Wu, 2020).

Initially, energy transition and pollution reduction were emphasized in the process of urban green development (Carlo Carraro et al., 2012). Hence, scholars attempted to evaluate green development by constructing a comprehensive index system (Godlewska and Sidorczuk-Pietraszko, 2019; Xiao et al., 2022). The indicators in the system include carbon dioxide emission (Wang and He, 2022), sulfur dioxide emission (Wang F et al., 2019), nitrogen dioxide emission (Liu Y et al., 2022), the amount of industrial wastewater discharged (Zhao et al., 2021), industrial smoke discharge (Wang M et al., 2019), etc. With the emergence of the "New Urbanism", the links between the economy, environment and society became the focus of urban green development (White and Ellis, 2007). As a result, measuring the urban green development purely from the perspective of pollutant emissions has been gradually abandoned, and scholars began to consider the coupling effect of economy, environment, and society. The common methods are data envelopment analysis (DEA) including super-efficient Slack Based Model (SBM) (Ding et al., 2022), the Energy Based Model (EBM) (Yang et al., 2022), stochastic Frontier analysis (SFA) (Shui et al., 2015), and stochastic non-parametric data envelopment analysis (StoNED) (Luo, 2022).

In recent years, elements such as human welfare, social welfare, equity, sharing, and integration have been incorporated into the research area of green development, which further expands the breadth and depth of green developmental research (UNEP, 2011). Based on the theory of "Ecology of Human Welfare," Wells points out that the pursuit of short-term economic and other benefits comes at the expense of long-term environmental losses that may eventually overshadow those benefits. In other words, the pursuit of one type of welfare endangers another (Wells, 1993). Wang et al. (2022) studied the level of green development in Chinese industry from the perspective of environmental welfare efficiency (EWE). They found that Industrial Productivity Efficiency (IPE) is much higher than EWE and that the improvement of EWE will be the key to the green transformation of Chinese industry (Wang and Li, 2020). Huang L et al. (2021) explored the impact of the sharing economy on green development based on the evolutionary game. The results show that the resource-sharing development model was more likely to achieve the equilibrium of the environmental game between firms and consumers than the factor input development model (Huang L et al., 2021).

On the other hand, studies on urbanization and economic development are more well documented (Henderson, 2003; Bloom et al., 2008; Dutt and Jaime Ros, 2008) and research on the relationship between urbanization and green development provides theoretical and practical value for quality urban development. At the same time, the urbanization process is a

systematic evolution and expansion process, a multidimensional concept that includes not only population urbanization, but also land urbanization and industrial urbanization. Existing studies have mainly explored the impact of a particular aspect of urbanization on GDE, for example, Zhu et al. (2019) studied the impact of industrial restructuring on GDE and concluded that both rationalization and advancement of industrial structure have a positive impact on GDE. Yanhua Guo et al. (2020) studied the impact of industrial agglomeration on green development and found a u-shaped relationship between industrial agglomeration and green development in Northeast China from 2003 to 2016. Some studies have also focused on the relationship between different elements and regional green development. Wang Z et al. (2022) analyzed the relationship between regional integration on urban green development efficiency (UGDE) in China, thus finding a spatial spillover effect of regional integration on UGDE. Zhang et al. (2018) found that technological innovation enhances UGDE and showed that there are regional and administrative level differences in UGDE. Feng and Chen, (2018) analyzed provincial GDE using a spatial Durbin model and found that different environmental regulations can have different effects on industrial GDE in China.

At present, China has proposed a series of new energy development and environmental intervention policies to promote urban green development. However, there is no evidence to support the impact of urban development on the GDE under China's macroeconomic policies at present. In addition, the existing researches still have the following deficiencies: (1) There is no unified index system to measure the urban GDE. (2) Generally, only the impact of urban industrial development on GDE is considered, while that of population inflow and urban expansion is ignored. (3) Most empirical studies focus on green development at the provincial level, with little evaluation of green development at the municipal level. To fill the research gap, this paper takes 41 cities in China's Yangtze River Economic Belt (YREB) city cluster as the research object. First of all, the index system of urban GDE is constructed based on the previous research. Second, SBM is used to obtain the urban GDE. Next, we use Tobit regression to examine the impact of three dimensions of urban development, namely, population urbanization, land urbanization, and urban industrial development, on GDE. In the end, the heterogeneity of GDE in different regions of YREB was analyzed. This study makes the following two contributions to the research related to urban green development. First, the measurement dimension of urban development was extended, which includes urbanization rate, urban built-up area rate, rationalization of industrial structure, and advancement of industrial structure. Second, we provide a comprehensive interpretation of the green development of the core cities in China's YREB and propose strategies for future development.

This study is divided into three steps and the research framework is shown in Figure 1.

The rest of the research is organized as follows. The second part provides information on the GDE measurement technique, the urban development indicator system, an integrated approach to examining how urban development affects GDE, and data. The third part reports the results of the empirical analysis. The fourth part discusses the calculation results and puts forward some policy recommendations. The fifth part is the main conclusion of this paper.

2 Materials and methods

2.1 Index system

2.1.1 Indicators of urban development

Previous studies only consider the impact of urban industrial development on GDE (Guo et al., 2020), but ignore other elements of urban development. For instance, population urbanization and land urbanization also affect the GDE. Based on the comprehensive consideration of the impact of urban development on green development and the existing urban development evaluation (Li et al., 2020), in addition to urban industrial development, population urbanization and land urbanization are also selected to measure urban development in this paper.

2.1.1.1 Population Urbanization

Population urbanization is measured by urbanization rate (UR), which is the proportion of the urban resident population to the total resident population in a certain country or region. It reflects the process and degree of population concentration in the urban area. The calculation formula is as follows.

$$UR = \left(\frac{UP}{UP + RP}\right) \times 100\% \tag{1}$$

Where UP represents the urban resident population in a certain city, RP represents the rural resident population.

2.1.1.2 Land Urbanization

Land Urbanization is a process of land use transformation in the urban area. In this paper, the built-up area rate (BAR) is used to measure land urbanization, which is the proportion of built-up area in the urban area. It reflects the extent of urban expansion. It is expressed by the formula as follows.

$$BAR = \frac{BA}{CA} \times 100\% \tag{2}$$

Where, BA represents the built-up area in a certain city, CA represents the area of the city.

2.1.1.3 Urban industrial development

Inspired by previous studies (Kraftova et al., 2016; Yu, 2017), this paper introduces the rationalization of industrial structure (RIS) and advancement of industrial structure (AIS) to measure urban industrial development. RIS and AIS portray the adjustment of industrial structure from two dimensions. RIS refers to the aggregate quality of the organic connection between industries. On the one hand, it is a response to the degree of coordination on the scale of production between industries; on the other hand, it is also a reflection of the degree of rational utilization of production factors. Using the method proposed by Ivana et al. and Gan et al. to measure the RIS, its formula is as follows.

$$RIS = 1 \Big/ \left[\sum_{i=1}^{n}\left(\frac{Y_i}{Y}\right)\left|\left(\frac{Y_i}{L_i}\right)\left(\frac{Y}{L}\right) - 1\right|\right] \tag{3}$$

Where Y represents the output value, L represents the number of employees, and i represents industry i, which is divided into

TABLE 1 Indicators of urban development.

Variable	Index	Measured methods	Unit
Population Urbanization	UR	Formula (1)	%
Land Urbanization	BAR	Formula (2)	%
Urban industrial development	RIS	Formula (3)	—
	AIS	Formula (4)	—

primary, secondary, and tertiary industries. It can be seen that the larger the RIS, the more reasonable the industrial structure.

AIS refers to the development of industrial structure from low level to high level, which is also a measure of industrial structure upgrading, specifically the development of tertiary industry (Han et al., 2017; Li et al., 2017). The ratio of tertiary sector GDP to secondary sector GDP is used to measure it, with the following formula.

$$AIS = \frac{Y_{it3}}{Y_{it2}} \tag{4}$$

Where, Y_{it3} represents the gross product of the tertiary industry in region i at time t; Y_{it2} represents the gross product of the secondary industry in region i at time t. The higher the value of AIS, the more advanced the industrial structure. Table 1 shows the measurement methods and units of urban development indicators.

2.1.2 Indicators of GDE

The measure of GDE usually adopts an input-output model, such as the DEA model and SBM model (Seiford and Zhu, 2002). However, there is no uniform standard for the selection of input and output variables. Generally, annual electricity consumption, annual electricity consumption, investment in fixed assets, capital stock, labor force, energy consumption and employment in the management of water conservancy and environment are used in input variables; industrial wastewater discharge, sulfur dioxide emissions, carbon dioxide emissions, GDP and total retail sales of consumer goods are used in output variables (Feng and Xu, 1999; Su et al, 2019; Zhang et al, 2021a; Zhang et al, 2021b). In this paper, six indicators with higher boundary contribution rates are selected to measure GDE among these indicators, as shown in Table 2. Descriptive statistics of these indicators are shown in Table A1.

2.2 Research method

2.2.1 SBM model

To overcome the defects of traditional models and more accurately measure the effectiveness of evaluation objects, Tone, (2001) proposed the non-radial and non-angle Slack Based Model (SBM). The results of efficiency measurement are not affected by the units used to measure input and output items. Input redundancy and output deficiency can be obtained under the premise of input minimization and output maximization at the same time. For production with m inputs and s outputs, we can obtain the possible set of production:

$$P = \left\{ (x, y) \,\middle|\, x \geq X\lambda, y \geq Y\lambda, \lambda \geq 0 \right\} \tag{5}$$

The SBM model is used to measure the efficiency of DMU (x_o, y_o) with m inputs and s outputs, then Eq. 6 describes the basic form of the SBM model:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s}\sum_{r=1}^{s} \frac{s_r^g}{y_{ro}}}$$

$$s.t. \sum_{i=1}^{m} x_{ij}\lambda_j + s_i^- = x_{io}$$

$$\sum_{r=1}^{s} y_{ij}\lambda_j - s_r^g = y_{ro}$$

$$\lambda, s^-, s^g, \geq 0$$

$$i = 1, 2, \ldots, m; r = 1, 2, \ldots, s; j = 1, 2, \ldots, n \tag{6}$$

Where ρ^* represents the efficiency value of DMU (x_o, y_o), s_i^- and s_r^g are slack variables, respectively representing the distance of expected output and input from the efficient Frontier; λ represents the weight; The left part of the equation in the model represents the technological Frontier or the efficient Frontier, while the right part represents the path through which the DMU is transformed into the efficient Frontier. The efficiency value $\rho^* \in (0, 1)$, the green development efficiency of the decision unit is on the effective Frontier when and only when $s_i^- = s_r^g = 0, \rho^* = 1$. An efficiency value less than 1 indicates that the DMU is inefficient or lacks efficiency.

2.2.2 Tobit model

Our explained variable GDE is a truncated data, ranging between 0 and 1, and any value above 1 is assigned a value of 1.

TABLE 2 Indicators of GDE.

Vector	No.	Index	Measured methods	Unit
Input Index	I1	Capital stock	Zhang et al. (2004)	10,000 RMB
	I2	Labor force	National statistical data	10,000 people
	I3	Energy consumption	National statistical data	10,000 tons
Output Index	O1	GDP	National statistical data	10,000 tons
	O2	Sulfur dioxide emissions	National statistical data	10,000 tons
	O3	Carbon dioxide emissions	Deng, (2016)	10,000 RMB

*National statistical data include China Statistical Yearbook and the China Urban Statistical Yearbook for 2010–2020.

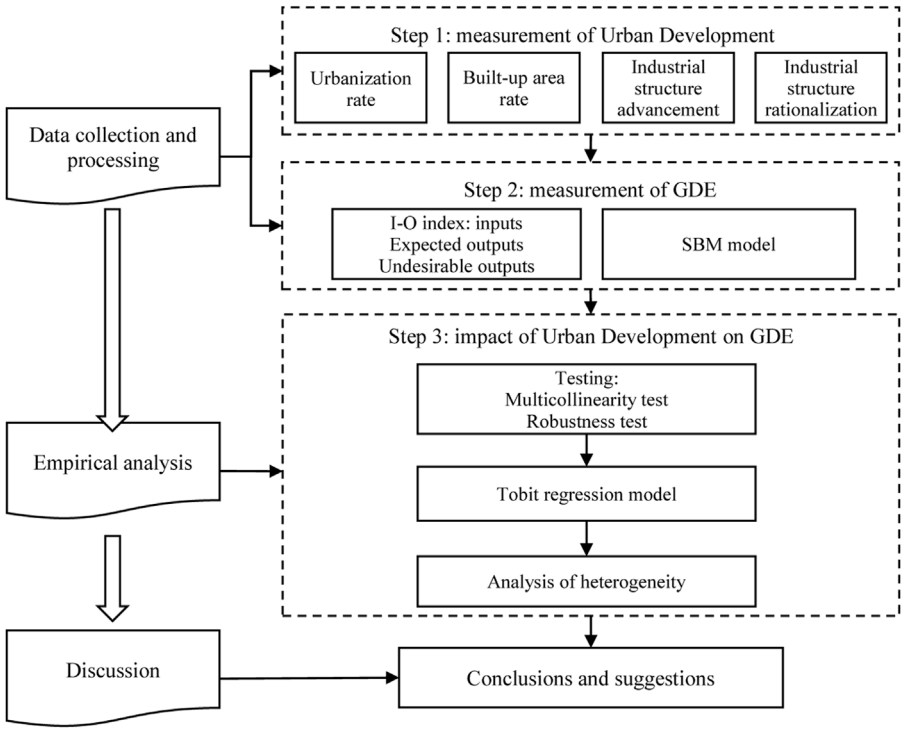

FIGURE 1
Research framework.

By common sense it should be normal data, but variables appear censored, all of which can be studied using the Tobit model (instead of the commonly used OLS linear regression).

The Tobit model was proposed by economist James Tobin in 1958, and it is a generalization of the Probit regression model. This model, also known as the restricted dependent variable model, is an econometric model proposed for explanatory variables for which the data are either discrete distributed or partially continuous. It solves the problem of linear regression with restricted dependent variables. The model is estimated using the great likelihood method, which can better avoid inconsistency and bias problems in the parameter estimation process. The specific model expressions are as follows.

$$y_i = \begin{cases} y_{i^*} = x_i\beta + \varepsilon, y_{i^*} > 0 \\ 0, y_{i^*} \le 0 \end{cases} \quad (7)$$

Where, x_i is the explanatory variable, y_{i^*} represents the explained variable, β is the regression parameter, and ε is the random disturbance term (Saglam, 2018). Tobit regression is mainly selected because the green efficiency value of the SBM model is between 0 and 1. Some observed data are compressed into one point. No matter whether using the whole sample or eliminating the sub-samples of discrete points, the OLS estimators are inconsistent, while the Tobit model can overcome this problem (Ma et al., 2017).

In this study, UR, BAR, RIS and AIS are used as explanatory variables. The explained variable is GDE. Tobit regression is used to examine the impact of urban development on GDE. In order to exclude the influence of other factors, frequently used control variables are also selected in this paper. In this paper, we choose panel Tobit mixed regression model. The model is defined as shown below.

$$GDE_{it} = \alpha_i + \beta_i UR_{it} + \gamma_i BAR_{it} + \delta_i RIS_{it} + \varepsilon_i AIS_{it} + \chi_i Control_{it} + \mu_{it} \quad (8)$$

Where, i is city and t is year, Control is the control variable, α is the regional unobservable effect, and μ is the random error.

2.3 Data

2.3.1 Research area

The paper takes the city cluster in YREB as the research object, and concentrates on 41 cities. These cities were chosen for the following reasons: firstly, they have complete statistics; secondly, their economies are relatively developed; thirdly, these cities are the main cities driving the economic development of the YREB. The upper reaches of the Yangtze River includes Chongqing, Luzhou, Panzhihua, Chengdu, Yibin, Guiyang, Zunyi, Anshun, Bijie; the middle reaches includes Huangshi, Ezhou, Wuhan, Jingzhou, Yichang, Xianning, Changsha, Yueyang, Yiyang, Nanchang, Jiujiang; the lower reaches includes Shanghai, Nanjing, Yangzhou, Zhenjiang, Suzhou, Wuxi, Changzhou City, Nantong, Taizhou, Hangzhou, Jiaxing, Huzhou, Ningbo, Shaoxing, Zhoushan, Hefei, Maanshan, Anqing, Tongling, Chizhou, Wuhu. These were chosen because they are the principal cities driving the urban YREB cluster's economic growth. In Figure 2, their precise locations are depicted.

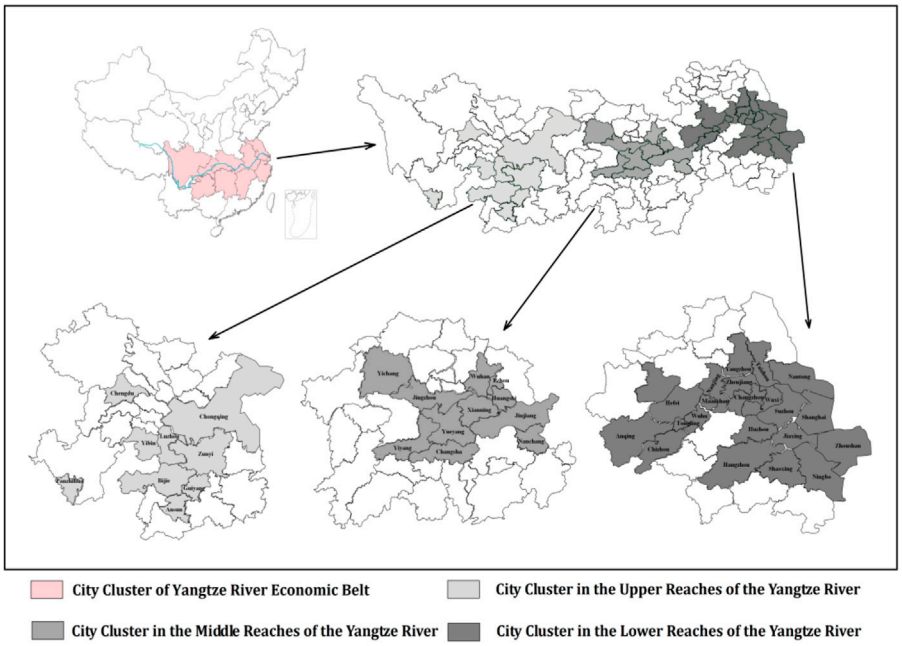

FIGURE 2
Research area.

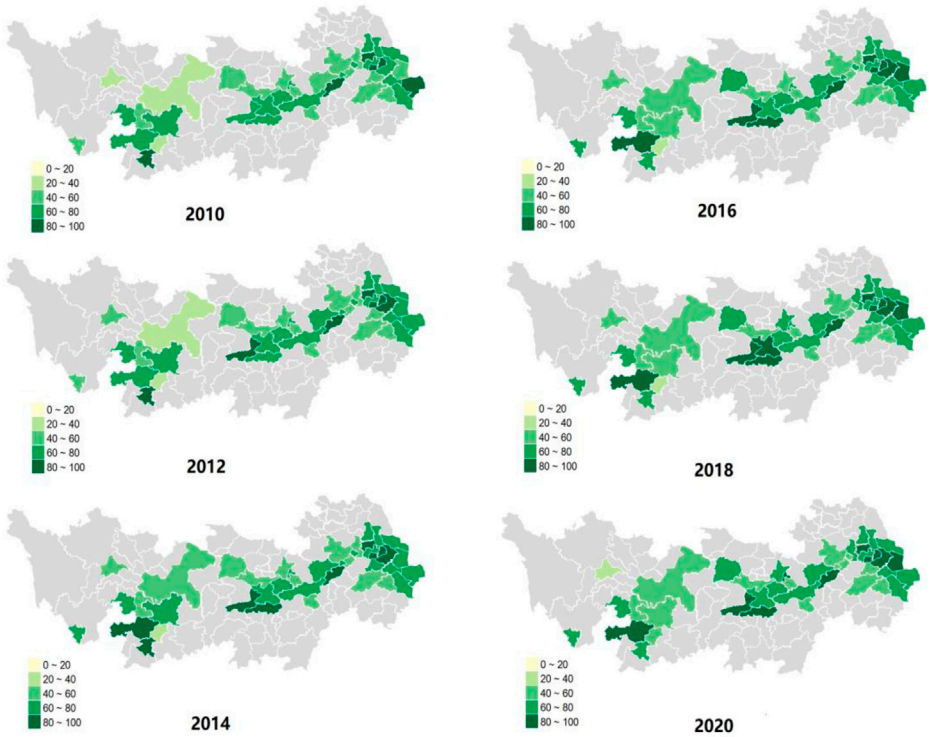

FIGURE 3
GDE from 2010 to 2020.

The YREB is one of the giant river basin economic belts in China with a large population, a large industrial scale and a very complete urban system. It is a strategic location for green development spanning the eastern, central and western regions of China. The YREB is a strategic support site for China's economic development and a major battleground for taking over the transfer of industries from coastal areas. The heavy industrial structure is characterized by a highly intensive layout of heavy chemical industries along the river, with the provinces and cities along the Yangtze River accounting for about 46% of the country's chemical output. At present, YREB's green development faces unprecedented problems such as industrial isomorphism, environmental pollution, low efficiency in using resources, unbalanced development, and inadequate development (Zhang et al., 2021a). On 14 November 2020, General Secretary Xi Jinping gave important instructions on the ecological and environmental protection of the YREB, to "promote the high-quality development of the YREB and write a new chapter of ecological priority and green development". It is of great significance to promote the development of the YREB along the path of ecological priority and green development, and to build it into a green economic demonstration belt with significant national impact.

2.3.2 Data collection

The explanatory variables are UR, BAR, RIS and AIS. They are calculated by Formula 1, 2, 3, 4 respectively, and their calculation results are shown in Figures A1, A2, A3, A4. All parameters in the formula were derived from China Statistical Yearbook and the China Urban Statistical Yearbook. Among them, Y, Y1, Y2, and Y3 are converted to constant prices in 2010. The explained variable is GDE which is calculated by Formula 6. The sources of each parameter in the equation are shown in Table 2. Besides the explanatory and explanatory variables, this paper introduces control variables to capture their effects on GDE (Chen et al., 2017; Sun et al., 2018). The control variables include environmental protection, government influence, openness, innovation level, and Policy Influence. The measurement methods of these variables are shown in Table 3. Descriptive statistics of these variables are shown in Table A2.

3 Impact of urban development on the GDE

3.1 GDE of the city cluster in the YREB

The GDE obtained by SBM model is shown in Figure 3. In 2010, the GDE of the city cluster in the upper reaches of Yangtze River is low and wide-ranging, increasing from north to south, ranging from 20% to 100%; the GDE of the city cluster in the middle reaches of Yangtze River is generally high and balanced, running the gamut from 40% to 80%; and the GDE of the city cluster in the lower reaches of Yangtze River is the highest, varying from 40% to 100%. Between 2012 and 2018, the GDE of the city cluster in the upper, middle and lower reaches of Yangtze River had all been improved. Among them, the GDE of the city cluster in the upper and middle reaches of Yangtze River has greatly increased; whereas, the eastern coastline region of the city cluster in the lower reaches of Yangtze River has seen a general improvement in GDE, but little change in its western region. In 2020, the GDE of the city cluster in the upper, middle and lower reaches of Yangtze River all exhibited a decline.

According to the calculation results of GDE, in 2010, the GDE of the city cluster in the upper reaches of Yangtze River is low and spans a wide range, while the city cluster in the middle reaches of Yangtze River overall had a slightly higher level and was more evenly distributed than the upper reaches. The city cluster in the lower reaches of Yangtze River had the highest level of GDE. This result is consistent with the findings of Zhu et al. (2019). In actuality, the economic development of each province in China's YREB is extremely uneven, with a general pattern of downward trend from east to west. The provinces and municipality in the lower reaches of the Yangtze River, including Anhui Province, Zhejiang Province, Jiangsu Province and Shanghai municipality, account for about 20%–30% of the country's total GDP between 2000 and 2010 (Wu, 2019; Zhang S. et al., 2019) and demonstrated a long period of high growth in the future (Zhang and Wu, 2006). In addition, the coastal provinces and municipalities in the lower reaches of the Yangtze River have attracted a large number of foreign capital and foreign enterprises (Fang G. et al., 2020). These capital and enterprises have improved the technological innovation and environmental protection standards in the area (Reddy et al.,

TABLE 3 Variables and definitions.

Variable	Symbol	Definition	Measured methods
Explained variables	GDE	Green Development Efficiency	Formula (6)
Explanatory variables	UR	Urbanization Rate	Formula (1)
	BAR	Built-up area rate	Formula (2)
	RIS	Rationalization of Industrial Structure	Formula (3)
	AIS	Advancement of Industrial Structure	Formula (4)
Control variables	EP	Environmental Protection	The logarithm of the ratio of environmental spending to GDP
	GI	Government influence	The logarithm of the ratio of fiscal spending to GDP
	OP	Openness	The amount of actual foreign capital used in the current year as a proportion of GDP
	IL	Innovation Level	The proportion of science and education expenditure to local fiscal expenditure
	PI	Policy Influence	Implementation of the New Environmental Protection Law: 0 before 2015, 1 after

2022). According to statistics, the innovation patents of Zhejiang province, Jiangsu province and Shanghai municipality alone accounted for more than 55% of the whole YREB in China in 2017, and this proportion was higher before 2017 (Hu S. et al., 2021). On the other hand, the fortune 500 companies here all require their Chinese suppliers to meet international environmental standards such as ISO 14000 including international environmental standards and corporate social responsibility standards (Lam, 2011). Economic development and the improvement of innovation capacity and management standards form a virtuous cycle, which promotes the GDE of the city cluster in the lower Yangtze River. On the contrary, the economic level of city cluster in the upper and middle reaches of Yangtze River were relatively backward coupled with more polluting enterprises, leading to a lower level of GDE.

Between 2012 and 2018, the GDE of the YREB city clusters all received a significant boost. Some studies suggest that this phenomenon is related to the macro policies of the Chinese government (Li G et al., 2021; Li J et al., 2021; Zhang et al., 2022). Our regression results also support the idea that PI is positively correlated with GDE. An interesting observation is that our results show a significant positive correlation between GDE and PI for the city cluster in the upper and middle reaches of Yangtze River, but not in the lower reaches. This means that the GDE of the city cluster in the upper and middle reaches of Yangtze River is more dependent on national policy regulation, while the lower reaches is more a result of the inherently high standards of technological innovation and environmental protection.

Our results further point to an overall downward trend in GDE for the YREB city clusters in 2020. The latest study considered the impact of the COVID-19 epidemic and rarely included data from 2020 in the analysis. In response to the findings obtained in this paper, we believe that a plausible explanation is that while both input variables and unexpected output declined during the epidemic, expected output (GDP) declined faster than they did (Dhar, 2020). As a result, the GDE of the YREB city clusters has declined.

TABLE 4 Impacts of urban development on the GDE in the YREB.

	City cluster in the YREB				
	Model 1	Model 2	Model 3	Model 4	Model 5
GI	−0.0355	−0.0702	−0.0238	−0.0294	−0.0491
	(−1.0027)	(−1.7678)	(−0.6747)	(−0.8290)	(−1.3579)
EP	0.0177	0.0164	0.0213	0.0252	0.0224
	(0.8835)	(0.8989)	(0.9524)	(1.1384)	(1.0121)
IL	−0.3589	−0.4685**	−0.3217	−0.4420**	−0.4029
	(−1.5919)	(−1.9902)	(−1.4282)	(−1.9760)	(−1.7900)
PI	0.0167	0.0344	0.0079	0.0113	0.0146
	(1.0424)	(1.9121)	(0.5024)	(0.7186)	(0.9181)
OP	−1.5166***	−1.1326***	−1.8834***	−1.8309***	−1.6506***
	(−4.3016)	(−2.7634)	(−5.0601)	(−5.2961)	(−4.6769)
UR		−0.1046			
		(−1.7428)			
BAR			0.8606***		
			(2.9868)		
RIS				0.6309***	
				(4.6429)	
AIS					0.0650**
					(2.4273)
cons	0.8073***	1.1649***	0.8307***	0.2272	0.7712***
	(7.6536)	(5.3888)	(7.4766)	(1.3790)	(7.1636)
N	451	451	451	451	451
F	6.0783	5.5339	6.5529	9.1556	6.0282

t statistics in parentheses.$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

3.2 Impact of urban development on the GDE

First, to test the multicollinearity of the data, the variance inflation factor (VIF) test was performed, as shown in Table A3. When VIF ≥10, it is generally accepted that there is a significant multicollinearity. It can be found that the VIF values of all variables in this paper are much less than 10, so there is no strong multicollinearity among the independent variables. The tests mentioned above lead to the conclusion that Eq. 8 is applicable to the analysis of the impact of urban development on the GDE. This paper employs clustering standard error regression, and the regression results are shown in Table 4. In order to verify the reliability of the results, this paper uses a robustness test for models 2 to 5 by changing the sample size, i.e., the data for 2010 and 2020 are removed. Table A4 presents the robustness test's findings. The results of the test are consistent with those of the original model, demonstrating the robustness and dependability of the original model's computed outputs.

Table 4 shows the impact of urban development on GDE in the YREB. Model 1 is the regression equation of control variables on the GDE. Models 2 to 5 display the regression results with various explanatory factors respectively. Among them, BAR (B = 0.8606, $p < 0.01$), RIS (B = 0.6309, $p < 0.01$) and AIS (B = 0.0650, $p < 0.05$) are significantly and positively correlated with GDE. It shows that the increase of urban land use as well as the optimization and upgrading of industrial structure will promote the efficiency of urban green development. On the other hand, UR (B = −0.1046, $p < 0.01$) is significantly and negatively correlated with GDE. It shows that the efficiency of urban green development will decline with the growth of urban population.

4 Heterogeneity test

Since there are some differences in the industrial structure, economic development level, scale of infrastructure construction and government management between the city cluster in the upper, middle and lower Yangtze River (Li-ming et al., 2022; Xie et al., 2022), heterogeneity analysis was conducted in this article. The regression results are presented in Tables 5, 6, 7, respectively.

TABLE 5 Impact of urban development on GDE in the upper reaches of the Yangtze River.

	Upper reaches of the Yangtze river			
	Model 2	Model 3	Model 4	Model 5
GI	−0.0173	0.2162**	0.2437**	0.3362***
	(−0.2091)	(2.3123)	(2.6217)	(3.4781)
EP	0.0154	−0.0607	−0.0462	−0.0434
	(0.3050)	(-1.0301)	(−0.7112)	(−0.7519)
IL	0.8746	1.2695**	1.3906**	1.6288**
	(1.4519)	(2.0784)	(2.2679)	(2.5043)
PI	0.0845***	0.0246	0.0110	−0.0010
	(3.6645)	(0.8598)	(0.4054)	(-0.0417)
OP	−0.8735	−1.3408	−1.9660*	−1.8262
	(−0.9585)	(−1.1190)	(−1.7600)	(−1.5831)
UR	−0.4763***			
	(−6.1463)			
BAR		−3.8982***		
		(−2.7679)		
RIS			−2.6822*	
			(−1.7458)	
AIS				−0.1496***
				(−2.6869)
cons	2.3196***	0.4432**	3.2234**	0.7206***
	(7.3416)	(2.1515)	(2.3007)	(4.3909)
N	99	99	99	99
F	36.7612	24.6173	22.8864	23.0876

t statistics in parentheses.$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 6 Impact of urban development on GDE in the middle reaches of the Yangtze River.

	Middle reaches of the Yangtze river			
	Model 2	Model 3	Model 4	Model 5
GI	−0.2535***	−0.1039*	−0.0658	−0.0675
	(−3.2254)	(−1.7328)	(−1.2650)	(−1.2442)
EP	0.0236	0.0256	0.0273	0.0344*
	(1.1544)	(1.3480)	(1.4785)	(1.8416)
IL	0.6837	0.7655	0.7444	0.7023
	(1.1642)	(1.3372)	(1.3349)	(1.1735)
PI	0.1156***	0.0419*	0.0300	0.0264
	(3.7948)	(1.6943)	(1.2772)	(1.0998)
OP	−0.1818	−1.1493	−1.2207	−1.9895***
	(−0.2559)	(−1.6586)	(−1.6360)	(−3.1477)
UR	−0.4158***			
	(−3.6558)			
BAR		−1.3416***		
		(−2.6370)		
RIS			−1.6735***	
			(−2.9372)	
AIS				0.0309
				(1.0572)
cons	1.8282***	0.5098***	2.2910***	0.6196***
	(5.0706)	(2.8376)	(4.1296)	(3.8484)
N	121	121	121	121
F	5.2736	5.7333	10.0621	2.9682

t statistics in parentheses.$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 5 shows the regression results for the city cluster in the upper reaches of Yangtze River. The findings demonstrate a significantly and negative correlation between UR (B = −0.4763, $p < 0.01$), BAR (B = −3.8982, $p < 0.01$), RIS (B = −2.6822, $p < 0.1$), and AIS (B = −0.1496, $p < 0.01$). It shows that the growth of urban population, the increase of urban land use, the optimization of industrial structure and the upgrading of industrial structure will all inhibit the efficiency of urban green development in the upper reaches of the Yangtze River.

The regression results of the city cluster in the middle reaches of Yangtze River are displayed in Table 6. The findings reveal a significantly and negative correlation between UR (B = −0.4158, $p < 0.01$), BAR (B = −1.3416, $p < 0.01$), and RIS (B = −1.6735, $p < 0.01$), but AIS is not significant at the level of 10%. Different from the upper reaches of the Yangtze River, the upgrading of urban industrial structure has no significant impact on the urban green development efficiency in the middle reaches of the Yangtze River, while the growth of urban population, the increase of urban land use and the optimization of industrial structure still inhibit the urban green development efficiency.

Table 7 presents the regression results for the city cluster in the lower reaches of Yangtze River. The results revealed that BAR (B = 0.7014, $p < 0.05$), RIS (B = 0.3763, $p < 0.05$) and AIS (B = 0.0949, $p < 0.01$) are significantly and positively correlated with GDE; while UR is not significant at the 10% level. It shows that the increase of urban land use as well as the optimization and upgrading of industrial structure in the lower reaches of the Yangtze River has the opposite effect on the urban green development as that in the upper and middle reaches, that is, they will promote the efficiency of urban green development. However, the increase of urban population has no significant impact on the efficiency of urban green development.

The UR and BAR of the city cluster in YREB demonstrate a significant negative correlation with GDE, indicating that population urbanization and land urbanization may generally inhibit the GDE. This phenomenon is particularly notable in the city cluster of upper and middle Yangtze River. Since 2010, land financing has played a significant role in generating these cities' tax

TABLE 7 Impact of the urban development on GDE in the lower reaches of the Yangtze River.

	Lower reaches of the Yangtze river			
	Model 2	Model 3	Model 4	Model 5
GI	−0.0841**	−0.0966**	−0.1062**	−0.1088**
	(−2.0141)	(−2.2655)	(−2.4435)	(−2.5626)
EP	0.0171	0.0183	0.0226	0.0230
	(0.8969)	(0.9338)	(1.1038)	(1.0708)
IL	−2.0650***	−2.0218***	−2.1339***	−2.0673***
	(−7.5097)	(−7.8811)	(−8.5736)	(−8.0832)
PI	0.0191	0.0203	0.0232	0.0198
	(0.9457)	(1.0216)	(1.1608)	(0.9946)
OP	−1.2547***	−1.2193***	−1.1768***	−0.9502**
	(−2.8780)	(−3.0226)	(−2.9596)	(−2.3839)
UR	0.0546			
	(0.8501)			
BAR		0.7014**		
		(2.2995)		
RIS			0.3763**	
			(2.5798)	
AIS				0.0949***
				(3.2274)
cons	0.8710***	1.0410***	0.6914***	0.9969***
	(2.9639)	(7.9518)	(3.3193)	(7.5999)
N	231	231	231	231
F	14.9487	15.9959	17.9805	17.4171

t statistics in parentheses.$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

revenues (Gu C et al., 2017), which has led to an increase in the rate of land urbanization. The accelerating pace of land urbanization has caused it to outpace economic growth (Chen M et al., 2013). In addition, in 2014, the Chinese government proposed the National New Urbanization Plan in order to increase the rate of population urbanization between 2014 and 2020. The urban population growth and urban area expansion increased the demand for land, water, electricity, coal, oil and natural gas, and also generated large amounts of urban waste and pollutants, thus increasing the environmental burden (Yao J et al., 2021). Finally, economic development and environmental capacity failed to afford the increase of energy consumption and pollution discharge caused by population urbanization and land urbanization, which led to the decrease of the GDE. This conclusion is similar to the findings of foreign studies. A series of studies have pointed out that uncontrolled urban expansion and green growth do not work well together. There is a clear negative correlation between population density and greenhouse gas emissions (Hoornweg, 2010; Kennedy, 2011; Khan, 2006). Typical examples are Atlanta and Barcelona, two cities with the same population but with a 28-fold difference in population per hectare and a four-fold difference in *per capita* greenhouse gas emissions. Cities with reasonable urban sprawl (e.g., Curitiba, Barcelona, Singapore) have significantly lower emissions *per capita* compared to cities with sprawl such as Albuquerque, Atlanta or Los Angeles (Zenghelis 2013). Conversely, unlike the cities in upper and middle reaches, the UR of the city cluster in the lower reaches of Yangtze River does not have a significant impact on the GDE. One plausible explanation is that the highly qualified personnel attracted by these cities indirectly affected GDE, such as indirectly improving the growth of regional economies and reducing management costs. Meanwhile, the GDE of the city cluster in the lower reaches of Yangtze River was improved in the process of land urbanization, and this finding is consistent with Li et al. (2022). In fact, Zhejiang Province, Jiangsu Province and Shanghai municipality in the lower reaches of Yangtze River have been the leaders of green development in China (Shan and Bi, 2012). The State Council has successively put forward some policies to improve urban green supporting facilities and urban landscaping in these regions since 2016, such as the Yangtze River Delta Urban Agglomeration Development Plan (2016) and the Yangtze River Delta Ecological and Green Comprehensive Development Demonstration Zone (2019). Therefore, these cities gave more consideration to environmental and ecological protection in the early days. These cities pay more attention to environmental and ecological protection in the process of land urbanization.

Several researches have revealed that both RIS and AIS show a significant positive correlation with GDE. These studies contend that along with the change in the driving force of economic development, there is a free flow of production factors between industries, such as labor and capital. This process will lead to the dynamic optimization of industrial structure, which is called the RIS (Jin and Li, 2013). At the same time, the industrial structure will gradually shift from the primary industry to the secondary and tertiary industries, and the industrial type will increasingly transform from labor and capital intensive industries to technology and knowledge intensive, that is, the AIS (Peneder, 2002). Through RIS and AIS, traditional industries with high energy consumption, low production capacity, and high pollution will be gradually replaced by new industries with high added value, high yield, and low pollution, thus increasing the GDE (Liang G et al., 2021). Using data from the United Kingdom, Jan Eeckhout shows that if large cities are energy-efficient ways of generating output, energy efficiency can be improved by encouraging urbanization and thus green living. In addition to the inherent impact of RIS and AIS on the GDE, the Chinese government has vigorously supported new energy and environmental industries during the 12th (2011–2015) and 13th (2016–2020) Five-Year Plans to address the impact of environmental pollution and climate change. According to statistics, the share of clean energy consumption in total energy consumption in China rises from 13.0% to 24.3% between 2011 and 2020. Meanwhile, China's annual investment in environmental industries is about RMB 100 billion (Zhao., 2010). Therefore, in general, the industrial development of the city cluster in YREB will promote GDE. However, the results of our heterogeneity analysis found the opposite effect in the city cluster of upper and middle Yangtze River. In fact, the industrial

structure of these cities is often low and relatively backward. It is difficult to ensure the matching of industrial development and resource structure when industrial adjustment is implemented blindly (Tang, 2019). What is more, it may absorb some enterprises with high energy consumption and low efficiency (Guo et al., 2020). Although the local government will regulate these enterprises, after comprehensively weighing the benefits of economic development and environmental protection, they are still inclined to choose deregulation to achieve economic growth (Wang and Shen, 2016).

The limitation of the study is that due to the availability of data, no mechanism testing was performed. It is also possible that urban growth is unplanned due to accidents such as natural disasters, and its impact on urban green development is unknown. Future studies could explore this issue in more depth. We hope you are satisfied with our modifications and explanations.

5 Conclusion

This research first constructs an index system of GDE. Then, we measure the GDE of the city cluster in YREB by SBM from 2010 to 2020. Finally, the Tobit model is used to measure the impact of urban development elements, namely, population urbanization, land use urbanization, and urban industrial development, on GDE and perform a heterogeneity analysis. The conclusions reached are as follows.

(1) Through the measurement, we discover that the GDE of the city cluster in YREB has generally been improved. Between 2010 and 2018, the GDE of the city cluster in YREB has improved, but in 2020, the GDE of the city cluster in YREB decreased.
(2) The policy has led to a general improvement in the GDE of the city cluster in YREB based on the second column of the full sample regression results.
(3) From the regression results of the upper and middle reaches of the Yangtze River, we can see that blindly promoting population urbanization and land urbanization can inhibit the GDE.
(4) The RIS and AIS have contributed to the GDE. However, the results of our heterogeneity analysis found that RIS and AIS of the city cluster in the upper and middle reaches of the Yangtze River showed a significant negative correlation with GDE to different degrees.

Based on these findings, the following suggestions are made.

First, a good policy can only realize its value if it is implemented properly. Accelerating the formation of green production methods and promoting the overall green transformation of economic and social development requires the implementation of cleaner production, the implementation of the basic state policy on resources and protection of the environment and the new environmental protection law.

Second, it is essential to avoid the situation that the economic development and environmental capacity failure to afford the increase of energy consumption and pollution discharge in the urban city. Hence, local governments need to promote energy transformation, increase environmental protection efforts and attract top-tier talent.

Finally, the promotion effect of RIS and AIS on the GDE, is a dynamic and slow process and requires a certain industrial foundation. If the relevant policies do not match the current industrial structure, the blind promotion of industrial restructuring will lead to a decrease in the GDE. The Chinese government needs to adopt industrial structure upgrading according to local conditions, respect the heterogeneity of green development in different cities. Formulate targeted and focused policy measures and focus on the development of a well-balanced economic and industrial structure. Avoid 'pulling out the seedlings' and 'one-size-fits-all' approach. At the same time, cities with high GDE should play a good role in demonstration and leadership, and cities with low GDE should be given more support in industrial transfer and environmental protection.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

ZS initiated the study. JH, TG, and JL collected the data and wrote the manuscript. JH and TG processed the data and performed statistical analysis. ZS revised the manuscript. All authors read and approved the final manuscript.

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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.

Publisher's note

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Appendix

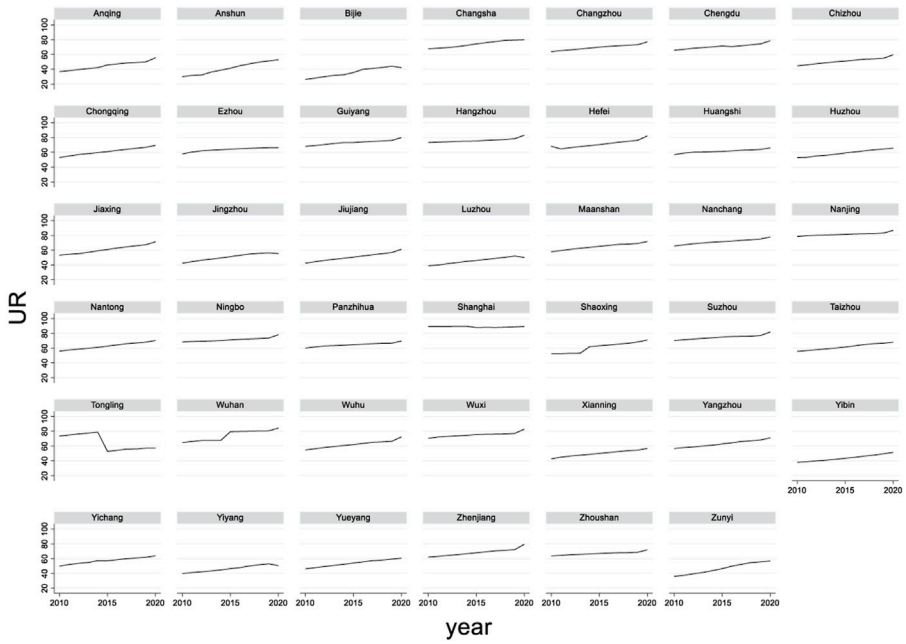

FIGURE A1
Urbanization rate.

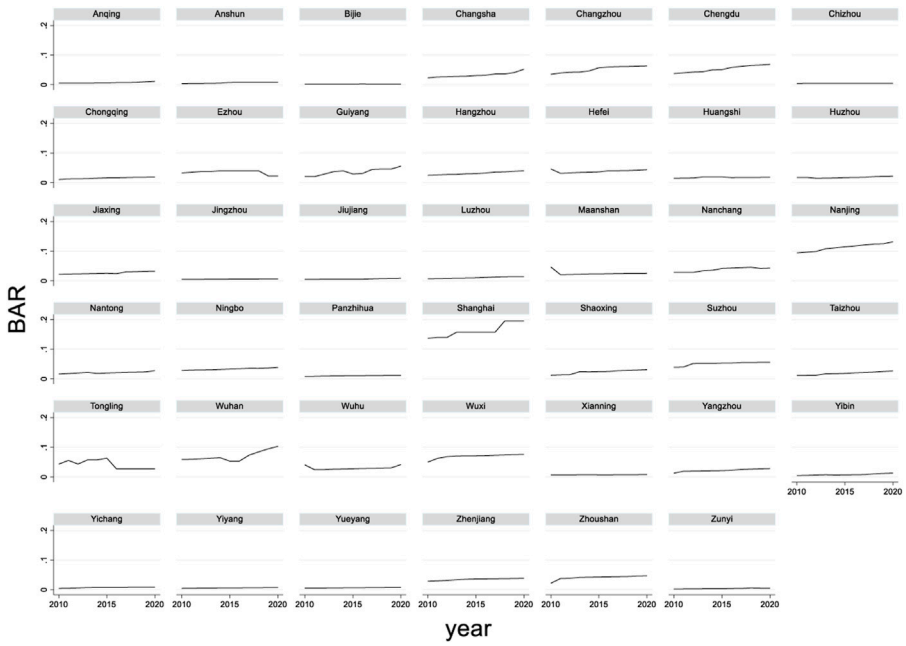

FIGURE A2
Urban built-up area rate.

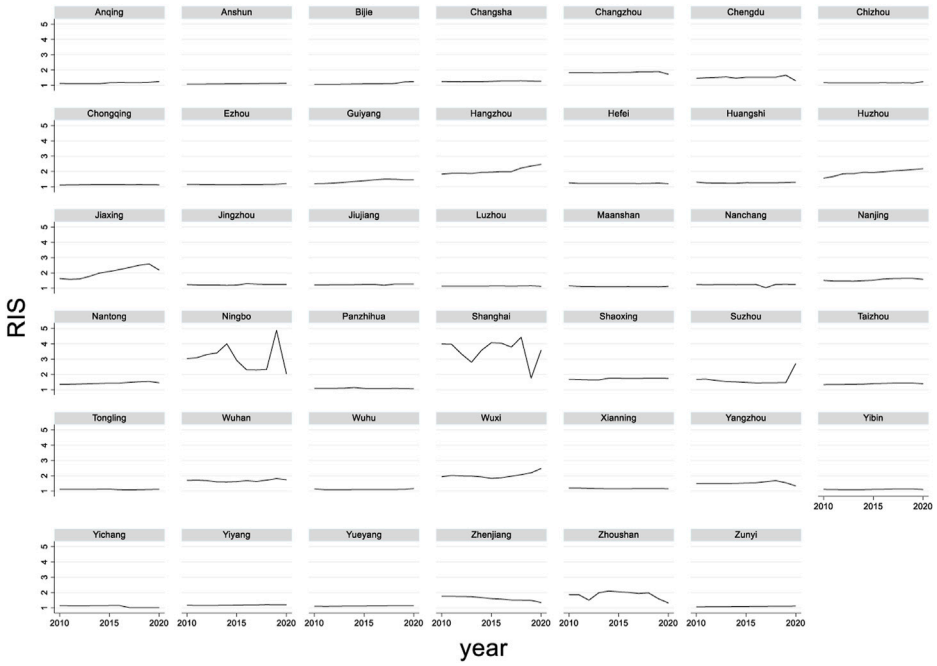

FIGURE A3
Rationalization of industrial structure.

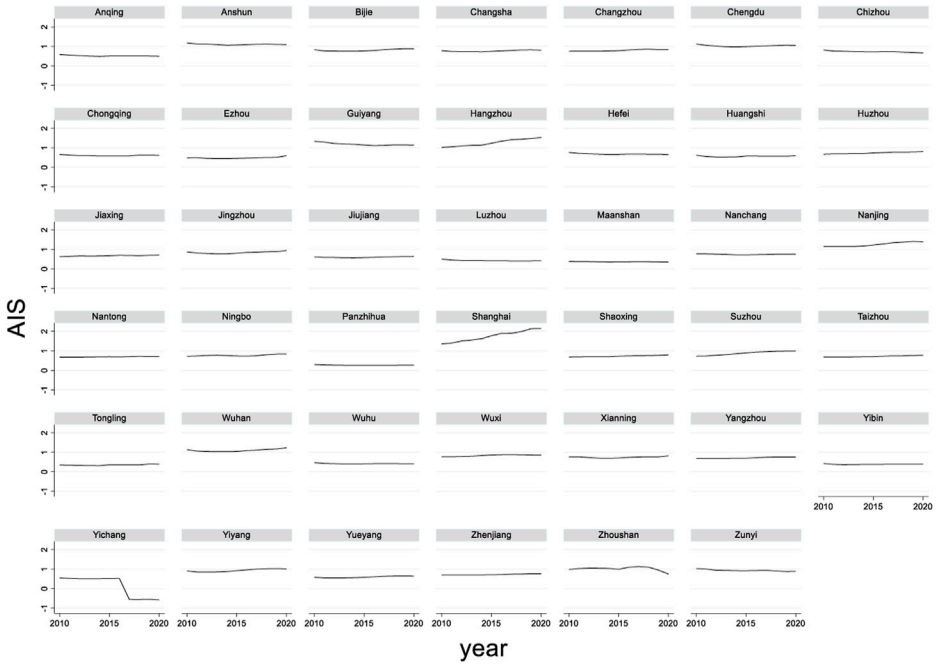

FIGURE A4
Advancement of industrial structure.

TABLE A1 Descriptive statistics of variables.

Variable	N	Mean	SD	Min	Max	Skewness	Kurtosis
Capital stock	451	1.073e+08	1.054e+08	3550937.529	7.242e+08	2.203	9.833
Labor force	451	114.234	156.201	7.100	1143.320	3.235	15.459
Energy consumption	451	354.991	531.981	5.009	3278.910	3.328	15.554
Sulfur Dioxide Emissions	451	53122.815	70873.158	1384.000	572747.000	4.285	26.882
Carbon Dioxide emissions	451	904957.067	1239739.310	97506.662	8834152.610	3.408	17.183
GDP	451	44891856.831	51223807.933	2328977.079	3.211e+08	2.381	10.011

TABLE A2 Descriptive statistics of variables.

Variable	N	Mean	SD	Min	Max	Skewness	Kurtosis
GDE	451	0.671	0.160	0.289	1.000	0.368	2.701
UR	451	61.936	12.676	26.180	89.600	−0.246	2.647
BAR	451	0.030	0.031	0.001	0.195	2.479	10.791
RIS	451	1.047	0.055	1.001	1.386	2.889	13.359
AIS	451	0.752	0.320	−0.580	2.145	0.390	6.972
EP	451	0.093	1.878	0.000	39.895	21.166	449.000
GI	451	0.157	0.060	0.076	0.371	1.211	4.300
OP	451	0.027	0.019	−0.000	0.093	0.761	3.218
IL	451	0.200	0.035	0.127	0.310	0.370	2.917
PI	451	0.545	0.498	0.000	1.000	−0.183	1.033

TABLE A3 VIF test results.

Model 2		Model 3		Model 4		Model 5	
Variable	VIF	Variable	VIF	Variable	VIF	Variable	VIF
UR	2.16	GI	1.46	GI	1.44	GI	1.49
GI	2.03	EP	1.31	EP	1.32	EP	1.32
PI	1.36	OP	1.18	OP	1.13	OP	1.11
OP	1.32	BAR	1.17	IL	1.11	IL	1.11
EP	1.30	IL	1.11	RIS	1.09	AIS	1.05
IL	1.16	PI	1.07	PI	1.05	PI	1.04

TABLE A4 Robustness test results.

	City cluster in the YREB			
	Model 2	Model 3	Model 4	Model 5
ln_UR	−0.1336*			
	(-1.9257)			
BAR		0.7836***		
		(2.6247)	0.5399***	
RIS	−0.0620	−0.0021		
			(4.2113)	
AIS				0.0697**
				(2.5546)
GI			−0.0087	−0.0289
	(−1.5264)	(−0.0716)	(−0.2924)	(−0.9731)
EP	0.0079	0.0099	0.0138*	0.0133*
	(1.0549)	(1.2419)	(1.7319)	(1.6494)
IL	−0.4276*	−0.1860	−0.2835	−0.2702
	(−1.6656)	(−0.7805)	(−1.2100)	(−1.1564)
PI	0.0314*	0.0080	0.0098	0.0114
	(1.7478)	(0.4875)	(0.5948)	(0.6890)
OP	−0.8250*	−1.6733***	−1.6173***	−1.4854***
	(−1.8422)	(−4.1927)	(−4.3672)	(−3.9604)
cons	1.2376***	0.7775***	0.2620*	0.7263***
	(4.9758)	(10.0093)	(1.7342)	(9.2498)
N	369.0000	369.0000	369.0000	369.0000
F	4.0658	4.8021	6.7122	4.8045

t statistics in parentheses* $p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

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Insurers' intervention, separation of two rights and firm's technology innovation

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This paper takes insurers' intervention as the entry point, and sets insurers' intervention, separation of two rights and firms' technological innovation in a specific context to study the transmission mechanism and economic consequences using panal model. The results show that there is a positive relationship between insurers' intervention and firm's technological innovation, and the degree of separation of two rights has a negative moderating effect on the relationship between insurers' intervention and technological innovation, and this effect is more obvious in the sample of state-owned enterprises. Therefore, the state should formulate relevant policies to guide the equity investment behavior of insurance companies so as to improve the operational efficiency of market resources.

KEYWORDS

insurance capital, insurance companies, technological innovation, separation of two rights, state-owned enterprises

1. Introduction

On August 16, 2019, People's Daily published "Insurance Funds Support the Real Economy and Technological Innovation through Stock Investment", which puts forward new requirements on the concept of insurance companies in capital investment to reasonably allocate capital resources and focus on the technological innovation development of enterprises, thus improving the ability of financial services to the real economy. So how insurance funds entering the stock market will affect the technological innovation ability of enterprises is a topic worth studying.

Technological innovation, as a long-term non-productive activity of the firm, gives public companies an advantage over the general firm because of the large number of investors and thus the risk transfer. However, this advantage is likely to be weakened in the face of the agency problem of separation of two rights between management, as the pursuit of short-term profit goals and the rise of risk will make them pay less attention to corporate governance, thus reducing the technological innovation activities of the company (1). In general, when there are only individual investors, most of the investment agents will "vote with their feet", being short-sighted and focused on short-term performance. However, when institutional investors join, the situation changes somewhat. Because institutional investors pay more attention to the long-term value of the company, especially the "hand voting" approach, they will participate in the internal governance of the company in order to pursue the long-term value of the company's development. In addition, institutional investors have some advantages, they have sufficient liquidity and abundant human resources to collect sufficient information to reduce the information asymmetry in R&D (2), so as to enhance the level of investment in R&D and thus improve the long-term value of the company.

Although institutional investors have many advantages, different types of investors still play different roles in strengthening the internal management of firms, for example, only focused investors strengthen corporate governance, while temporary investors are counterproductive (3). And institutional investors do not necessarily strengthen corporate governance in 1990, and their relatively frequent transactions are not conducive to the long-term management of the firm. Bushee (4) further found that: when the shareholding of institutional investors is high, company managers are less likely to reduce R&D expenditures, thus increasing the technological innovation capacity of the company; at the same time, when the turnover rate is high and the market is dominated by impulsive investors, managers will reduce R&D investment, thus preventing the risk of profit downside. However, the impact of market sentiment may not reduce the company's financial stability and market share (5). So insurance companies, as important institutional investors, how do they affect technological innovation in the process of internal governance of the company after their participation in the company? Through what mechanisms when they act on technological innovation in the face of the different separation of two rights and agency problems of the company? This question is worth studying.

Therefore, this paper puts insurers' intervention, separation of two rights and technological innovation in one context and finally finds that the relationship between insurers' intervention and technological innovation is positive, and the degree of separation of two rights has a negative moderating effect on the relationship between insurers' intervention and technological innovation, and this effect is more pronounced in the SOE sample.

The contributions of this paper is as follows: Firstly, many papers have studied the relationship between institutional investors and enterprises from the perspective of institutional investors, and less from the perspective of insurance companies, but this paper enriches the study of the relationship between insurance companies' equity investments and capital markets. Third, the findings of this paper provide some empirical references for insurance companies to further plan their equity investment capital allocation to serve the development of the real economy.

2. Literature review, theoretical analysis and research hypothesis

Institutional investors have been major players in emerging capital markets and are important in terms of their influence on corporate governance, which can affect firms' investment decisions (6). As for the research on institutional investors and technological innovation, some scholars believe that institutional investors can promote technological innovation (7–9), mainly through the improvement of corporate governance (10), which is mainly reflected in the fact that institutional investors supervise and manage the company and thus improve the efficiency of the company's operations, and when the higher the shareholding of institutional investors, the less they reduce the company's R&D expenditure (4), which may be for the maintenance of established interests. As an important institutional investor, one of the important operations of insurance companies is information gathering and control measures to achieve efficient information management and risk management to minimize the cost of risk (11). The insurance companies have a strong data base and customer base, and they are gradually equipped with data mining capabilities in the process of self-competition in the insurance industry (12). And institutional investors have more positive behavioral motivations (13), which are crucial for promoting corporate governance, and are more likely to generate more original innovations in the capital market (14). And the increased confidence in the market is more helpful to the company's insurance business, contributing to the positive development of the market (15). In these idiosyncratic contexts, once an insurance company participates in the stock, it will first strengthen the internal governance and supervision of the company, and guide the company to make more accurate R&D investment decisions and improve the efficiency of capital allocation. At the same time, the higher the percentage of insurance participation, the more they will focus on the long-term development of the company, and will not easily withdraw the funds invested in R&D, which will guarantee the sustainability of R&D and increase the company's technological innovation.

However, investors are irrational, and institutional investors are no exception (16). Insurance companies may have a narrow view and thus can be driven by interest to influence managers to make short-term decisions that only increase short-term profits (17). Collusion with managers' interests can make the asymmetry of information disclosure more pronounced, especially in insurance companies where the contagion effect caused by information asymmetry is more severe (18). Asymmetric information can directly affect a company's investment decisions and have a direct impact on business performance. However, institutional investors tend to spend less on R&D when the company's operating performance is poor (4). Therefore, when the insurance company appears to collude with the interests of the company's management, it is likely to have information asymmetry, which generates excessive liability risk and thus affects the investment decisions of the company, and if the company's performance declines at this time, it is likely to reduce its R&D expenditures even if the company's shareholding ratio is high, otherwise it will affect the loss of greater interests. So what kind of influence do insurance companies have on corporate technology innovation? Therefore, the following competing hypotheses are proposed.

H1a: Insurers' intervention will promote the development of firm's technological innovation.

H1b: Insurers' intervention will inhibit the development of firm's technological innovation.

Compared with the mature capital market environment in Europe and the United States, the second type of agency problem of controlling shareholders manipulating the management of the company through the advantage of equity concentration is more serious in the special market environment and governance model in China. In the second type of agency problem, the ultimate controlling shareholders' control as well as cash flow rights of listed companies at the corporate governance level may deviate (19), hoping to gain a larger control and thus control the listed company with a very small cash flow right, indicating that the

separation of two rights problem is more serious in Chinese listed companies. From the ultimate profit pursuit of shareholders, some scholars argue that the degree of separation of two rights plays a positive role in corporate technological innovation. From the risk diversification hypothesis, it is believed that the degree of separation of two rights helps major shareholders to diversify their risks and thus diversify their investments, which positively affects the R&D activities of enterprises on the basis of financial stability; and from the hollowing out theory under the pyramid structure, in the context of capital market innovation as a hot spot, major shareholders may passively increase R&D funds for technological innovation in order to meet the market hot spot. Therefore, it is believed that the separation of two rights will increase the technological innovation ability of enterprises (20). Moreover, although the rise of institutional investors will lead to the increase of equity concentration, they will effectively manage the agency problem (21), especially a small number of institutional investors own most of the company's shares, and they will strengthen supervision and management for their own interests and improve the efficiency of all aspects of the company's investment. Therefore, after the involvement of insurers, they will strengthen corporate governance through external supervision and other actions, especially paying high attention to the innovative behaviors related to the company's performance, thus improving the company's technological innovation capacity in general.

However, changes in the internal institutional environment of the company will affect the technological innovation capability of the company, and the technological innovation capability of the company will show an increase and then decrease during the change of the institutional environment from low to high, and the higher separation of two rights will also weaken the influence of the internal institutional environment on technological innovation (22), so the degree of separation of two rights may weaken the technological innovation capability (23). From the perspective of differences in the ownership structure of ultimate controllers, Chen et al. (24) argue that the degree of separation of two powers has a significant encroachment effect on the development of technological innovation and can produce significant distortions in the efficiency of corporate innovation. From the perspective of small and medium-sized listed companies, due to the scarcity of resources, shareholders generally engage in investments with high certainty and low risk, but major shareholders will engage in profit-making behaviors such as "tunneling", which will invariably capture the company's profits, thus negatively affecting the development of technological innovation (25). After the insurer's acquisition, it may collude with the management of the listed company to seize the company's profit, which makes the company's internal governance low and its investment decision making ability decrease, and the level of technological innovation will not be improved. So the following hypothesis is proposed.

H2a: The degree of separation of two rights has a positive moderating effect on the relationship between insurers' intervention and technological innovation.

H2b: The degree of separation of two rights has a negative moderating effect on the relationship between insurers' intervention and technological innovation.

Compared with mature foreign markets, the most fundamental characteristic of Chinese listed companies is the state-owned enterprise background. The unique property rights nature of SOEs gives them a different role orientation. Most SOEs' decisions and actions are not aimed at purely economic interests, but rather at maximizing national interests, maintaining economic development, and social stability. As the largest shareholder, state-owned shareholders will form a certain conflict of interest and threat to other shareholders, which will create a certain information asymmetry problem and agency conflict. The major shareholders will engage in related transactions and appropriation of funds for their own interests, which will inevitably harm the interests of small and medium shareholders and further cause agency conflict, and the optimal allocation of resources cannot be better. The agency problem of separation of two rights in SOEs is more prominent than in private enterprises, and the opportunistic behavior of managers will have a greater impact on the behavior of institutional investors. In SOEs with more severe agency problems, the degree of separation of two rights plays a more significant effect on the relationship between insurers' intervention and technological innovation. Therefore, the following hypothesis is proposed.

H3: The moderating effect of the separation of two rights on insurers' intervention and technological innovation is more pronounced in SOEs relative to the private enterprise sample.

3. Study design

3.1. Sample selection and data sources

In order to avoid the impact of major accounting standard revisions, this paper selects the data of A-share listed companies from 2007 to 2018 as the sample for research and analysis, and follows the following principles: (1) financial listed companies are excluded; (2) companies marked ST or *ST in the year are excluded; (3) some companies with missing data; (4) in order to exclude the influence of extreme values, all continuous variables are used at the 5% level. The financial data were obtained from CSMAR database and RESSET financial database, and cross-checked.

3.2. Model construction and variable definition

3.2.1. Variable definition

(1) Technological innovation. Referring to Chang et al. (26)'s study, this paper uses the number of corporate patents as a proxy variable for corporate technological innovation. Technological innovation measured in this paper refers to the cumulative number of patents applied for, obtained, granted or accepted as of the end of the reporting period, and is logarithmically processed.

(2) Insurers' intervention. If the listed company has insurance company's participation, IP = 1, otherwise IP = 0; SP then indicates the percentage of insurance company's participation.

(3) Separation of two rights. Since agency conflict is mainly caused by the inconsistency of agent and principal's objectives, which leads to principal-agent problems and conflicts, the

TABLE 1 Definition of variables.

Variable	Variable description
LnTI	Logarithm of the cumulative number of patents applied for, obtained, granted or accepted as of the end of the reporting period
IP	Whether the insurance company participates in the stock, if so, 1, otherwise, 0
SP	Insurance company's shareholding ratio
SPRT	The degree of separation of two rights, i.e., the difference between control and ownership
SOE	Nature of listed company, if state-owned,1, otherwise, 0
TQ	Tobin's Q = (market value of owner's equity + total book value of debt) / book value of total assets, i.e., the market value of the company as a proportion of the replacement cost of assets, if >1 indicates that the purchase of capital goods for the expansion of production is profitable, more investment is added; otherwise, the investment will be reduced
CFLOW	Free cash flow = (operating profit + depreciation and amortization)/total assets at the beginning of the year
SALES	Sales ratio = sales revenue / total assets at the beginning of the year
TOER	Change of hands ratio = Volume of stock traded during the year/Number of A shares circulating
LEV	Gearing ratio = Total liabilities at the end of the period/Total assets at the end of the period
BTM	Book-to-market ratio = Total assets at the end of the period/(market value of equity + market value of net debt)
ROA	Return on Assets = EBITDA / Total Assets at the end of the period
SIZE	Asset size, as the natural logarithm of total assets at the end of the period
Year	Annual dummy variables
Indu	Industry dummy variables

TABLE 2 Descriptive statistics results.

Variable	Mean	Std.Dev.	Min	Max
LnTI	4.975	5.352	1.610	6.724
IP	0.094	0.292	0	1
SP	0.001	0.003	0	0.012
SPRT	4.2	6.7	0	20.4
TQ	2.418	1.701	0.445	6.689
CFLOW	0.022	0.012	0.005	0.049
SALES	0.236	0.427	−0.303	1.401
TOER	1.778	1.011	0.402	4.085
LEV	0.382	0.199	0.077	0.743
BTM	0.701	0.555	0.15	2.248
ROA	0.062	0.04	−0.005	0.148
SIZE	21.731	1.058	20.281	24.183
SOE	0.323	0.468	0	1
TAT	0.614	0.308	0.213	1.367

separation degree of two rights of control and ownership is selected as the agency variable of agency conflict in this paper. As shown in Table 1 is variable definition.

3.2.2. Model construction

In order to verify the relationship between insurers' intervention and firm's technological innovation, this paper proposes to construct the following models: firstly, we test the relationship between insurers' intervention and firm's technological innovation through model (1) and model (3) to test hypothesis 1; next, we test the effect of the degree of separation of two rights on the relationship between insurers' intervention and technological innovation through model (2) and model (4) to test hypothesis 2 and hypothesis 3.

$$LnTI_t = \beta_0 + \beta_1 IP_t + controls + year + indu + \varepsilon \quad (1)$$

$$LnTI_t = \beta_0 + \beta_1 IP_t + \beta_2 SPRT_t \times IP_t + controls + year + indu + \varepsilon \quad (2)$$

$$LnTI_t = \beta_0 + \beta_1 SP_t + controls + year + indu + \varepsilon \quad (3)$$

$$LnTI_t = \beta_0 + \beta_1 SP_t + \beta_2 SPRT_t \times SP_t + controls + year + indu + \varepsilon \quad (4)$$

4. Analysis of empirical results

4.1. Descriptive statistics results

The results of descriptive statistics in Table 2 show that the standard error of enterprises in technological innovation is 5.352, which indicates that the heterogeneity of technological innovation varies very much among enterprises and the distribution of innovation results is very uneven; the standard deviation of the degree of separation of two rights is 6.7, which indicates that the

TABLE 3 Test of the relationship between insurers' intervention and technological innovation.

	LnTI			
	(1)	(2)	(3)	(4)
IP	0.4013***	0.1524*		
	(0.0904)	(0.0725)		
SP			33.6115***	15.8366*
			(8.6476)	(7.7660)
TQ		0.0854*		0.0861*
		(0.0483)		(0.0483)
CFLOW		−3.6519		−3.6646
		(4.5977)		(4.5974)
SALES		0.1452		0.1468
		(0.1161)		(0.1160)
TOER		−0.0932*		−0.0922*
		(0.0523)		(0.0523)
LEV		0.3500		0.3427
		(0.4092)		(0.4085)
BTM		0.0053		0.0084
		(0.1635)		(0.1634)
ROA		−2.1316		−2.1569
		(1.6475)		(1.6472)
SIZE		0.6042***		0.6060***
		(0.0835)		(0.0830)
SOE		−0.0435		−0.0445
		(0.1384)		(0.1383)
SPRT		−0.9317		−0.9403
		(0.7629)		(0.7631)
TAT		0.4361**		0.4398**
		(0.2036)		(0.2036)
_cons	2.6933***	−10.7720***	2.7002***	−10.8152***
	(0.0277)	(1.7343)	(0.0276)	(1.7246)
Year	YES	YES	YES	YES
Indu	YES	YES	YES	YES
R^2	0.0028	0.0978	0.0021	0.0979
N	3,381	3,381	3,381	3,381

Standard errors are in brackets below the coefficients, and *, **, and ***represent significant at the 10, 5, and 1% levels, respectively.

heterogeneity of the difference between control and ownership of each company is relatively large; while the mean value of IP is 0.094 and the standard error of 0.292 indicates that the proportion of insurers' intervention in listed companies is still relatively large; the standard error of 0.003 for SP indicates that the variation in the proportion of insurers' intervention is not obvious.

4.2. Main test results

Table 3 reports the test of the relationship between insurers' intervention and technological innovation with LnTI as the explanatory variable and IP and SP as the explanatory variables, where both columns (1) and (3) do not control for year and industry effects, and both columns (2) and (4) control for year and industry effects. The coefficients of IP and SP in columns (1) and (3) are positive and both are significant at the 1% level of significance, while the coefficients of IP and SP in columns (2) and (4) are both positive and both are significant at the 10% level of significance. This indicates that the involvement of insurers positively contributes to the technological innovation of firms. This may be due to the fact that insurance companies, as important institutional investors in the market, have more positive behavioral motivations and strong information gathering and risk management capabilities, which in turn will influence the investment decisions of companies, especially to invest more in R&D, thus improving the level of technological innovation of companies. Hypothesis H1a is tested.

Table 4 reports the test of the relationship between insurers' intervention, separation of two rights and technological innovation with LnTI as the explanatory variable and IP and SP as the explanatory variables, where both column (1) and column (2) control for year and industry effects. The coefficients of IP and SP in columns (1) and (2) are positive and significant at the 1% level of significance, while the coefficients of IP_SPRT (the interaction term between IP and SPRT) and SP_SPRT (the interaction term between SP and SPRT) are negative and significant at the 1% level of significance. This indicates that although the involvement of insurers increases the technological innovation capacity of the firm, the separation of two rights negatively moderates the relationship between it and technological innovation. This is because although insurers have a positive incentive to effectively supervise the company and provide proper guidance in investment decisions to help improve the company's technological innovation capability, but with a high degree of separation of two rights, the company will not have enough capital to invest in R&D. The insurance company will not consider the long-term development goals of the listed company for its own development, on the contrary will collude with the company's management to the company's interests, and the tunnel effect is obvious, which will eventually be detrimental to the company's overall performance growth. At the same time, the R&D investment is reduced and enters a vicious cycle process, and the level of technological innovation naturally declines. Hypothesis H2b is supported.

Table 5 reports the regression results for the sub-sample of SOEs and private firms on the relationship between insurers' intervention, separation of two rights and technological innovation, with LnTI as the explanatory variable and IP and SP as the explanatory variables, where columns (1)–(8) control for year and industry effects. Columns (1)–(4) are for SOEs and columns (5)–(8) are for private firms. The coefficients of IP and SP in columns (1) and (3) are positive but insignificant, the coefficients of IP and SP in columns (2) and (4) are positive and significant at the 5% and 10% levels of significance, respectively, the coefficient of IP_SPRT (interaction term between IP and

TABLE 4 Test of the relationship between insurers' intervention, separation of two rights and technological innovation.

	(1)	(2)
	LnTI	LnTI
IP	0.2648*	
	(0.1486)	
IP_SPRT	−2.0689*	
	(1.0388)	
SP		21.8119*
		(10.4361)
SP_SPRT		−1.05*
		(0.6184)
TQ	0.0848*	0.0858*
	(0.0482)	(0.0482)
CFLOW	−3.6435	−3.6513
	(4.5905)	(4.5943)
SALES	0.1442	0.1464
	(0.1161)	(0.1161)
TOER	−0.0929*	−0.0923*
	(0.0523)	(0.0524)
LEV	0.3429	0.3377
	(0.4088)	(0.4082)
BTM	0.0008	0.0067
	(0.1635)	(0.1635)
ROA	−2.1082	−2.1421
	(1.6485)	(1.6484)
SIZE	0.6060***	0.6069***
	(0.0835)	(0.0830)
SOE	−0.0424	−0.0443
	(0.1384)	(0.1384)
SPRT	−0.6013	−0.7709
	(0.7947)	(0.7931)
TAT	0.4380**	0.4421**
	(0.2032)	(0.2035)
_cons	−10.8270***	−10.8449***
	(1.7332)	(1.7244)
Year	YES	YES
Indu	YES	YES
R^2	0.0984	0.0981
N	3,381	3,381

Standard errors are in brackets below the coefficients, and *, **, and ***represent significant at the 10, 5, and 1% levels, respectively.

SPRT) is negative but insignificant, and the coefficient of SP_SPRT (interaction term between SP and SPRT) is negative and significant at the 10% significance level, while the coefficients of IP, SP, IP_SPRT, and SP_SPRT in columns (5)–(8) are insignificant. This indicates that the negative moderating effect of separation of two rights on insurers' intervention and technological innovation is more pronounced in the SOE sample. In SOEs, the agency problem is more severe and more likely to involve insurers in collusive behavior with management's interests, thus engaging in opportunistic speculative behavior, and inefficient investment decisions will inevitably be detrimental to the development of firms' technological innovation capabilities. Further support is provided for hypothesis H3.

4.3. Robustness tests

In order to prevent endogeneity problems caused by sample selection bias, this paper further adopts the PSM method to select paired samples of companies by the propensity score (PS), and conducts radius matching, kernel matching and nearest neighbor matching respectively to test the relationship between "insurers' intervention, separation of two rights and firm's technological innovation". Eight firm characteristics variables, such as book-to-market ratio (BTM), free cash flow (CFLOW), asset-to-liability ratio (LEV), return on assets (ROA), sales ratio (SALES), asset size (SIZE), Tobin's Q (TQ), and turnover ratio (TOER), were selected to test the relationship between "insurers' intervention, separation of two rights, and firm technological innovation" to build propensity models. Logit models were used to estimate the propensity score value (PS value) for each company's two power separation and to test the differences of the dependent variables between the two sample groups. Table 6 shows the results of the PSM test, and the t-value tests for the pre- and post-matching samples are not significant and the differences are small for either matching method. Further support is provided for hypothesis 1 and hypothesis H2a.

Meanwhile, since the separation of two rights has an important relationship with the equity structure, the equity concentration indicator (the first largest shareholder's shareholding) is selected instead of SPRT for the robustness test, and Table 7 is the result of the robustness test, which is consistent with the results of the previous study.

5. Conclusion and policy recommendations

Technological innovation as a non-investment activity of enterprises, listed companies have certain advantages. But this advantage is likely to be weakened by the agency conflict of separation of two rights, and in the context of capital market innovation as a hot spot, it is an inevitable requirement for companies to improve their technological innovation capability as a result of the development of internal and external environment. As an important institutional investor in the market, how will

TABLE 5 Regression results for the sub−sample of SOEs and private enterprises.

	LnTI							
	SOE = 1				SOE = 0			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
IP	0.2800	0.4198**			0.0041	−0.0018		
	(0.1754)	(0.2003)			(0.1700)	(0.2209)		
IP_SPRT		−3.4857				0.0872		
		(2.1284)				(2.1093)		
SP			22.3000	32.6903*			8.0156	5.6236
			(17.3113)	(19.8268)			(15.9976)	(20.9657)
SP_SPRT				−2.52*				34.4754
				(1.2711)				(191.7803)
TQ	0.0706	0.0656	0.0725	0.0688	0.0579	0.0578	0.0584	0.0581
	(0.0938)	(0.0933)	(0.0938)	(0.0932)	(0.0591)	(0.0592)	(0.0592)	(0.0592)
CFLOW	2.0212	2.3385	2.1134	2.3678	−8.6211	−8.6155	−8.6178	−8.5953
	(6.9702)	(6.9670)	(6.9673)	(6.9775)	(6.0597)	(6.0709)	(6.0554)	(6.0668)
SALES	0.1563	0.1596	0.1582	0.1607	0.1236	0.1237	0.1252	0.1255
	(0.1831)	(0.1820)	(0.1827)	(0.1823)	(0.1502)	(0.1502)	(0.1504)	(0.1504)
TOER	−0.0740	−0.0740	−0.0728	−0.0735	−0.1252**	−0.1253**	−0.1224*	−0.1226*
	(0.0967)	(0.0969)	(0.0967)	(0.0967)	(0.0626)	(0.0627)	(0.0627)	(0.0627)
LEV	−0.4535	−0.4749	−0.4644	−0.4840	1.2721**	1.2725**	1.2754**	1.2773**
	(0.7078)	(0.7027)	(0.7072)	(0.7025)	(0.5186)	(0.5188)	(0.5170)	(0.5169)
BTM	0.1011	0.0928	0.1030	0.0989	−0.3476	−0.3477	−0.3430	−0.3431
	(0.2199)	(0.2201)	(0.2198)	(0.2201)	(0.2454)	(0.2454)	(0.2451)	(0.2450)
ROA	−1.3549	−1.2967	−1.3532	−1.2980	−2.5354	−2.5350	−2.5576	−2.5571
	(2.6419)	(2.6445)	(2.6427)	(2.6447)	(2.1050)	(2.1051)	(2.1055)	(2.1056)
SIZE	0.7854***	0.7867***	0.7948***	0.7962***	0.4254***	0.4252***	0.4218***	0.4212***
	(0.1246)	(0.1243)	(0.1234)	(0.1231)	(0.1178)	(0.1184)	(0.1172)	(0.1176)
SPRT	−1.1713	−0.5152	−1.1803	−0.7289	−0.7153	−0.7274	−0.7227	−0.7732
	(1.3013)	(1.3213)	(1.3011)	(1.3162)	(0.9402)	(0.9921)	(0.9399)	(0.9880)
TAT	0.4195	0.4106	0.4228	0.4203	0.4987*	0.4983*	0.5038*	0.5019*
	(0.3051)	(0.3038)	(0.3059)	(0.3054)	(0.2676)	(0.2675)	(0.2677)	(0.2674)
_cons	−14.7701***	−14.8133***	−14.9834***	−15.0262***	−6.8773***	−6.8721***	−6.8211***	−6.8031***
	(2.7268)	(2.7189)	(2.7003)	(2.6942)	(2.3808)	(2.3956)	(2.3722)	(2.3819)
Year	YES	YES	YES	YES	YES	YES	YES	YES
Indu	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.1578	0.1594	0.1572	0.1581	0.0716	0.0716	0.0718	0.0718
N	1,361	1,361	1,361	1,361	2,020	2,020	2,020	2,020

Standard errors are in brackets below the coefficients, and *, **, and ***represent significant at the 10, 5, and 1% levels, respectively.

the involvement of insurance companies affect technological innovation? What is the effect of the separation of two rights of the company on their relationship? This paper analyzes the relationship between insurers' intervention, separation of two rights and technological innovation using the data of listed companies from 2007 to 2018 as the research sample. The results show that insurers' intervention has a positive relationship with the technological innovation output of companies, and has a positive mediating effect on technological innovation by affecting agency costs, and this effect is more obvious in the sample of state-owned enterprises. This is mainly because the participation of insurance companies in listed companies will have a positive effect on technological innovation through the supervision and management of the companies, thus affecting their performance improvement and increasing their R&D investment; however, due to the serious agency conflict problem in Chinese listed companies, the management will involve the institutional investors in their collusion group and will not focus on the long-term

TABLE 6 PSM regression results.

	LnTI					
	Radius matching		Kernel matching		Nearest neighbor matching	
	(1)	(2)	(3)	(4)	(5)	(6)
IP	0.2807*		0.2807*		0.2807*	
	(−0.147)		(−0.148)		(−0.148)	
IP_SPRT	−2.4971*		−2.4972*		−2.4970*	
	(−1.3292)		(−1.3293)		(−1.3291)	
SP		23.1943*		23.1943*		23.1942*
		(−13.3619)		(−13.3619)		(−13.3617)
SP_SPRT		−1.52*		−1.52*		−1.51*
		(−0.7513)		(−0.7513)		(−0.7512)
TQ	0.0789	0.0805*	0.0789	0.0805*	0.0789	0.0805*
	(−0.0485)	(−0.0487)	(−0.0483)	(−0.0487)	(−0.0486)	(−0.0487)
CFLOW	−2.2302	−2.3154	−2.2302	−2.3154	−2.2302	−2.3154
	(−4.4738)	(−4.4791)	(−4.4738)	(−4.4791)	(−4.4738)	(−4.4791)
SALES	0.0871	0.0886	0.0871	0.0886	0.0871	0.0886
	(−0.1142)	(−0.1145)	(−0.1143)	(−0.1145)	(−0.1145)	(−0.1145)
TOER	−0.0971*	−0.0957*	−0.0971*	−0.0957*	−0.0971*	−0.0957*
	(−0.0524)	(−0.0525)	(−0.0524)	(−0.0525)	(−0.0524)	(−0.0525)
LEV	0.5314	0.522	0.5314	0.522	0.5314	0.522
	(−0.3926)	(−0.3923)	(−0.3928)	(−0.3923)	(−0.3927)	(−0.3923)
BTM	0.005	0.006	0.005	0.006	0.005	0.006
	(−0.1651)	(−0.1653)	(−0.1651)	(−0.1653)	(−0.1651)	(−0.1653)
ROA	−1.0455	−1.0787	−1.0455	−1.0787	−1.0455	−1.0787
	(−1.5857)	(−1.5848)	(−1.5856)	(−1.5848)	(−1.5858)	(−1.5848)
SIZE	0.5893***	0.5905***	0.5893***	0.5905***	0.5893***	0.5905***
	(−0.082)	(−0.0825)	(−0.085)	(−0.0825)	(−0.083)	(−0.0825)
SOE	0.0082	0.0124	0.0082	0.0124	0.0082	0.0124
	(−0.1344)	(−0.1344)	(−0.1344)	(−0.1344)	(−0.1344)	(−0.1344)
_cons	−10.3784***	−10.4110***	−10.3784***	−10.4110***	−10.3784***	−10.4110***
	(−1.7125)	(−1.7046)	(−1.7125)	(−1.7046)	(−1.7125)	(−1.7046)
Year	YES	YES	YES	YES	YES	YES
Indu	YES	YES	YES	YES	YES	YES
R^2	0.0955	0.0950	0.0954	0.0951	0.0953	0.0951
N	3381	3381	3381	3381	3381	3381

Standard errors are in brackets below the coefficients, and*, **, and ***represent significant at the 10, 5, and 1% levels, respectively.

development and strategic investment of the companies, which will be detrimental to the development of technological. The findings of this paper are useful for strengthening the internal equity of companies, and have profound implications for strengthening the internal equity structure of companies and state regulation of the capital market.

In the end, this paper proposes the following recommendations: (1) as an emerging capital market, China's various operation mechanisms are still unsound, and no effective restraint mechanism has been formed for listed companies, so effective external supervision should be carried out for the loopholes in the development of listed companies, especially the agency conflict of separation of two rights; (2) the internal governance structure of listed companies should be improved to form relatively effective institutional constraints, and an effective governance system should be formed for agency conflicts, especially the behavior of

TABLE 7 Robustness tests.

	LnTI			
	(1)	(2)	(3)	(4)
IP	0.1524*	0.0682*		
	(0.0825)	(0.0367)		
IP_TOPHLD		−0.5742*		
		(0.2478)		
SP			15.8366*	6.1695*
			(8.7660)	(3.6793)
SP_TOPHLD				−26.1016*
				(15.7961)
TQ	0.0854*	0.0826*	0.0861*	0.0848*
	(0.0483)	(0.0479)	(0.0483)	(0.0479)
CFLOW	−3.6519	−3.5891	−3.6646	−3.6243
	(4.5977)	(4.5989)	(4.5974)	(4.5989)
SALES	0.1452	0.1430	0.1468	0.1463
	(0.1161)	(0.1163)	(0.1160)	(0.1162)
TOER	−0.0932*	−0.0923*	−0.0922*	−0.0918*
	(0.0523)	(0.0521)	(0.0523)	(0.0522)
LEV	0.3500	0.3550	0.3427	0.3436
	(0.4092)	(0.4091)	(0.4085)	(0.4085)
BTM	0.0053	0.0022	0.0084	0.0075
	(0.1635)	(0.1632)	(0.1634)	(0.1634)
ROA	−2.1316	−2.1182	−2.1569	−2.1543
	(1.6475)	(1.6474)	(1.6472)	(1.6471)
SIZE	0.6042***	0.6009***	0.6060***	0.6048***
	(0.0835)	(0.0837)	(0.0830)	(0.0831)
SOE	−0.0435	−0.0476	−0.0445	−0.0469
	(0.1384)	(0.1381)	(0.1383)	(0.1378)
TAT	0.4361**	0.4312**	0.4398**	0.4379**
	(0.2036)	(0.2038)	(0.2036)	(0.2040)
_cons	−10.7720***	−10.6929***	−10.8152***	−10.7858***
	(1.7343)	(1.7379)	(1.7246)	(1.7269)
Year	YES	YES	YES	YES
Indu	YES	YES	YES	YES
R^2	0.0978	0.0980	0.0979	0.0980
N	3,381	3,381	3,381	3,381

Standard errors are in brackets below the coefficients, and *, **, and ***represent significant at the 10, 5, and 1% levels, respectively.

controlling shareholders should be strictly restrained to prevent their "emptying" of the company's internal interests; (3) for institutional investors such as insurance companies, the country should provide effective policy guidance and constraints to avoid collusion of interests between insurance companies and company management, so as to ensure effective corporate governance and investment management, avoiding the waste of financial resources and improving the efficiency of capital allocation.

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

BX: conceptualization, writing-review, and editing. FH: conceptualization, methodology, and writing-original draft. All authors contributed to the article and approved the submitted version.

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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.

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Air pollution, residents' concern and commercial health insurance's sustainable development

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As Chinese residents are increasingly concerned about environmental and health issues, the importance of commercial health insurance has come to the fore. Therefore, it is necessary to study the relationship and mechanism between air pollution and commercial health insurance. This paper empirically analyzes the impact and mechanism of air pollution on the sustainable development of Chinese commercial health insurance. The analysis is conducted using the IV-probit and IV-tobit models with thermal inversion as the instrumental variable for air pollution, with Chinese households as the study population and 2018 as the study period. The results show that $PM_{2.5}$ concentration has a positive and significant effect on both household participation in commercial health insurance and the level of participation, and that residents' concern is an important channel linking air pollution and commercial health insurance, where pollution reporting plays a negative transmission role, protective behaviors play a positive transmission role, and healthy depreciation plays a positive transmission role. The results of this study contribute to the comprehensive development of China's social security system and the sustainable development of the commercial health insurance market.

KEYWORDS

air pollution, commercial health insurance, sustainable development, thermal inversions, pollution reporting, protective behaviors, healthy depreciation

1 Introduction

Since the occurrence of several severe haze events in China in 2013, the issue of air pollution has become an issue of great concern for Chinese residents, second only to corruption (Wike and Parker, 2015). In 2014, China treated haze as a natural calamity that endangers public health. Haze pollution consists mainly of $PM_{2.5}$ pollution, and the Chinese government believes that the first step in combating air pollution is to control $PM_{2.5}$ concentration. China has also clearly stated in its 14th Five-Year Plan that it will continue to improve environmental quality, enhance awareness of the ecological and environmental protection of society as a whole, and comprehensively fight the battle against pollution. With China's increased efforts to combat environmental pollution, the country's air pollution problem has been gradually addressed and the concentration of air pollutants is gradually decreasing every year; however, there are still many areas where air pollution remains a serious problem. According to the 2019 national air quality figures released by China's

Ministry of Ecology and Environment, 46.6% of the 337 prefecture-level cities met ambient air quality standards, compared to 24.85% in 2016, a considerable improvement but still less than half. Air pollution is not only a matter of national image and economic growth, but also a constant threat to public health.

The impact of air pollution on the physical and mental health of the population cannot be underestimated, as it can directly or indirectly cause short-term and even long-term damage to the human body, increasing the risk of human health issues (Archsmith et al., 2018), such as a shortening life expectancy *per capita* (Chen et al., 2013; He et al., 2016), inducing respiratory diseases (Chay and Greenstone, 1999; Moretti and Neidell, 2009) and increasing the chance of lung cancer (Brunekreef and Holgate, 2002). The effects of air pollution on human health are not only physiological, but also psychological, as residents may experience negative emotions, such as anxiety and depression, as a result of air pollution (Tian et al., 2015; Kim et al., 2020; Pun et al., 2017). In addition to the physical and psychological harm, air pollution also increases the burden of medical costs on residents (Jerrett et al., 2003; Narayan and Narayan, 2008; Zhang et al., 2008; Hou et al., 2012) and reduces family wellbeing (Levinson, 2009; Luechinger and Raschky, 2009; Ferreira et al., 2013). In order to address these issues, commercial health insurance is an effective way to protect the health interests of residents, in addition to combating environmental pollution (Graff Zivin and Neidell, 2013). Commercial health insurance helps to alleviate the pressure on residents' associated medical costs (Fisher, 2003), is an important way to reduce the financial burden of the medical treatments associated with air pollution, and assists in improving family wellbeing (Hadley and Waidmann, 2006). There are numerous studies on environmental pollution and residents' health, but in the research system of the impact of air pollution on commercial health insurance, there is little discussion on the mechanism of air pollution on commercial health insurance. We refer to the relevant literature (Zhang et al., 2018; Ito and Zhang, 2020; Sun et al., 2021a) and then investigate the mechanism of residents' concern as a potential channel for air pollution to affect commercial health insurance.

It is therefore important to study the relationship and mechanism between $PM_{2.5}$ and commercial health insurance participation, not only to help residents understand the negative effects of air pollution so that countermeasure policies can be formulated to improve household welfare, but also to provide a reference for the sustainable development of commercial health insurance for insurance companies.

The main contributions of this paper are as follows: First, in this paper, in order to investigate the relationship between air pollution and household participation behaviors in commercial health insurance, we have used China Household Finance Survey (CHFS) data from a micro perspective to investigate whether air pollution leads households to increase the likelihood and extent of spending on commercial health insurance. Second, we explored the mechanisms of air pollution, residents' concern and commercial health insurance by using residents' concern as a potential channel, providing new perspectives and experiences for mechanism research in this direction. At the same time, the above findings help the comprehensive development of China's medical system and social security system to provide benefits to residents, and moreover, help insurance companies to understand the influencing factors and mechanisms of commercial health insurance products, which are conducive to the sustainable development in commercial health insurance.

2 Literature

With the rapid economic and technological development of modern society, the consumption of environmental resources has become costly and the physical and mental health of the residents has been affected, while highlighting the importance of commercial health insurance (Gong et al., 2019). The role played by commercial health insurance in reducing the cost of healthcare for residents has also contributed to its rapid growth. However, the rapid growth of China's commercial health insurance market has been accompanied by the unhealthy development of commercial health insurance, such as the problem of unbalanced distribution of insurance resources and regions, and the problem of commercial health insurance becoming a luxury that is difficult for low-income residents to consume (Li, 2022). In order to solve the above problems, it is particularly important to identify the factors influencing commercial health insurance, which can contribute to the healthy development of the commercial health insurance market and make an important contribution to improving the social healthcare system (Wu et al., 2020). In order to find out what factors influence commercial health insurance, scholars have conducted a large number of empirical and theoretical studies. The collection and accumulation of the above literature on the factors influencing commercial health insurance will help us to examine the body of empirical research on commercial health insurance and to refine the missing variables.

Early scholars provided detailed summaries of the influences on health insurance, broadly grouped into three main categories: economic, social and legal-political. In addition, a number of scholars have explored new influencing factors (Zietz, 2003; Hussels et al., 2005; Outreville, 2013). In the following, we present some studies on the factors influencing the purchase of commercial health insurance. Using data from individual community micro-surveys to examine the impact of residents' risk attitudes and self-assessed health (SAH) on the purchase of voluntary private health insurance (VPHI), it was found that SAH has a negative impact on VPHI (Tavares, 2020). An empirical study based on data from the Chinese General Social Survey (CGSS) and a Probit model found that household internet use significantly increased the likelihood of purchasing commercial health insurance (Xu et al., 2022). In addition to these results, other studies in the literature have found that educational level, marital status and social health insurance also have an impact on commercial health insurance (Cofie et al., 2013; Xiao, 2018; Li et al., 2021). By combining our research on the factors influencing commercial health insurance, we have added influencing factors such as internet use, risk attitude, educational level, marital status and social health insurance. This completes our empirical study and effectively addresses the problem of omitted variables.

Few studies have examined the impact of air pollution on commercial health insurance, and we have only collected the following six papers. Chang et al. (2018) examined insurance policy data from insurance companies and found that severe air pollution led residents to purchase insurance, but when air pollution decreased, residents dropped their insurance. Pi et al. (2019) used data from the China Health and Retirement Longitudinal Study (CHARLS) to examine the relationship between air pollution and household insurance coverage for each type of insurance. Zhao (2020) used CHFS data to examine the relationship between air pollution and household insurance coverage; Chen and He (2021) used CHARLS data to examine the effect of air pollution on health insurance coverage, again using individual health status as a potential channel; Wang et al. (2021) used CHFS data to examine the relationship between air pollution and commercial health insurance; Jia and Yan (2022) used CHFS data to examine the effect of haze pollution on commercial health insurance. Most of the above literature studies on air pollution and commercial health insurance use CHFS data, which indicates that CHFS is a good help for studying the relationship between air pollution and commercial health insurance. Commercial health insurance in China includes four types of insurance, of which long-term care insurance is a non-health insurance. Most of the above studies do not exclude long-term care insurance from commercial health insurance, which may affect the accuracy of the estimation results. There is also little and incomplete discussion of the mechanisms by which air pollution affects commercial health insurance. Our study has two important innovations over previous studies: First, we exclude long-term care insurance from commercial health insurance to make the estimation results more accurate; second, we classify the potential channels into pollution reporting (before the risk occurs), protective behaviour (when the risk occurs) and health depreciation (after the risk occurs) based on risk management theory, and conduct a more comprehensive mechanism analysis.

3 Hypothesis

Environmental pollution includes a range of issues such as air pollution, soil pollution, water pollution, noise pollution and light pollution (LoPalo and Spears, 2022). Compared to other pollution issues, the high mobility of air makes it more likely that residents will be exposed to air pollution, and residents will suffer greater impacts and harm from air pollution (Manisalidis et al., 2020), which may even lead to respiratory diseases and lung cancer (Turner et al., 2020), and may also increase residents' anxiety or mental illness caused by excessive psychological stress, etc (Bruyneel et al., 2022; Balakrishnan and Tsaneva, 2023). We know that air pollution affects the physical and mental health of residents, and that risk management is needed when households are exposed to air pollution risks. Risk management theory divides risk into before, during and after the risk occurs. Before the risk occurs, households may invest in healthcare to improve their health to resist the hazards of air pollution, or move to areas with better air quality, etc.; when the risk occurs, households may make protective investments such as buying air purifiers, green plants and masks, *etc.*,; after the risk occurs, households are already affected by air pollution and incur certain medical expenses. In addition to the basic protective function of social health insurance, the next best thing is to invest in commercial health insurance. The long-term or short-term effects of air pollution on household members will increase the likelihood that households will purchase commercial health insurance, while the effect of commercial health insurance will increase as the cost of medical care rises. Therefore, we propose the following hypotheses.

Hypothesis 1a: Air pollution will have a positive effect on the likelihood of household participation in commercial health insurance.

Hypothesis 1b: Air pollution will have a positive effect on the level of household participation in commercial health insurance.

Residents' perceptions of the risks posed by air pollution are complex and vary to some extent (Cori et al., 2020; Li et al., 2022). When residents receive information about air pollution and deal with it according to their own perceptions, they are influenced by a number of factors, which are ultimately reflected in their risk management actions (Sereenonchai et al., 2020). Based on risk management theory, we divide air pollution risks into before, during and after (Généreux et al., 2019). Residents perceive the risk at different stages of its occurrence, are concerned about it and will react differently. First, before air pollution risks occur. Residents choose to report pollution in order to improve their living environment and to protect their health capital from the harmful effects of air pollution (Xu et al., 2021). Residents expend energy and costs to report pollution in their area *via* phone, We Chat, the Internet and other means to achieve risk mitigation. This approach can reduce protective investments, medical costs and insurance costs caused by air pollution. Second, when the risk of air pollution occurs. At this point, residents feel that their physical and mental health is being affected by air pollution. In order to protect themselves and their families from the dangers of air pollution, residents may choose to increase their protective investments against air pollution, such as buying air purifiers, masks, greenery, new air systems, etc (Zhang and Mu, 2017). Since residents are already feeling the effects of air pollution, they may choose to purchase commercial health insurance to reduce subsequent medical costs. Third, after the risk of air pollution has occurred. Air pollution has already damaged residents' physical and mental health, causing them to fall ill and incur medical costs. When faced with high medical costs, residents may choose to purchase commercial health insurance to reduce high medical costs in similar situations in the future (Lee and Lee, 2019). The above three potential channels all indicate that residents observe the phenomenon and hazards of air pollution, pay different levels of attention to it, and take different risk management measures, but all with the ultimate aim of preventing and reducing the risks of air pollution. Based on the above analysis, the following hypotheses are proposed in this section.

Hypothesis 2a: Pollution reporting plays an inverse role in the impact of air pollution on commercial health insurance.

Hypothesis 2b: Protective behaviors plays a positive role in the impact of air pollution on commercial health insurance.

Hypothesis 2c: Health depreciation plays a positive role in the impact of air pollution on commercial health insurance.

4 Data and methods

4.1 Data sources and variable selection

4.1.1 Data sources

This paper focuses on the impact of air pollution on household commercial health insurance purchasing behaviour. The data on household commercial health insurance purchasing behaviour are obtained from the 2019 China Household Finance Survey (CHFS). The 2019 CHFS household survey sample uses data from 2018 and covers a sample of 107,008 individuals in 34,643 households from 29 provinces and 343 counties in China, except Xinjiang, Tibet, Taiwan, Hong Kong and Macau. The 2019 CHFS micro data on household finance is very comprehensive, containing a large number of individual and household characteristics, such as total income, total assets, total expenditure, age, gender, place of residence, education level, etc. This provides a rich selection and support for the empirical research in this paper.

The 2019 CHFS data was selected for two reasons: 1) the 2019 CHFS data were up-to-date and current; and 2) the 2019 CHFS data has a breakdown of the types of commercial health insurance, with four types of commercial medical insurance, critical illness insurance, income protection insurance, and long-term care insurance. This facilitates the exclusion of non-illness-related insurance, allowing for more accurate estimates of the impact of air pollution on household commercial health insurance participation behavior, as well as obtaining a clearer mechanism.

Air pollution and thermal inversion data were obtained from NASA's MERRA-2 product. The 2018 p.m.$_{2.5}$ data and thermal inversion data obtained were matched with the 2019 CHFS data based on the prefecture-level cities, and processed to obtain a valid sample size of 32,645.

4.1.2 Variable selection

(1) Air pollution (*pollution*)

Air pollution data is very complex and difficult to obtain, with five common classifications of air pollutants: $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO. Due to the wide range of air pollutants, China set up an Air Quality Index (AQI) to measure the level of air pollution. These air pollution data are basically obtained from ground-based monitoring stations, and may be subject to manipulation (Ghanem and Zhang, 2014; Sullivan et al., 2017) and may also cause bias problems when conducting empirical studies. To address this issue, some scholars have used satellite remote sensing monitoring data, which has a long time span, covers a wide range of areas and is not subject to manipulation, thus avoiding the problem of bias (Li and Zhang, 2019). Whereas ground-based monitoring stations have limited access to data, satellite remote sensing data are raster data, allowing access to air pollutant data for the entire residential area or study area, and are therefore more representative and complete (Zhang et al., 2017). Most scholars use satellite remote sensing data from the National Aeronautics and Space Administration's (NASA's) MERRA-2 product (Deschenes et al., 2020; Chen et al., 2022), which has global coverage of remote sensing data and records atmospheric signature data from 1980 to the present.

Based on the above analysis, we chose to use $PM_{2.5}$ data from NASA's MERRA-2 product for 288 prefecture-level cities in China in 2018 as the air pollution variable. The raster data was extracted using ArcGIS 10.8 based on the administrative area of each prefecture-level city, and the obtained data was used to perform an inverse extrapolation of $PM_{2.5}$ (Buchard et al., 2016) with the following formula:

$$PM2.5 = DUST2.5 + SS2.5 + BC + 1.4 \times OC + 1.375 \times SO4 \quad (1)$$

$PM_{2.5}$ is the main cause of haze pollution (van et al., 2010). $PM_{2.5}$ pollutants are small in diameter, tend to carry more toxic substances compared with other types of pollutants, and hover in the air for a relatively longer period of time, making it easier for them to penetrate indoors and have an impact on human health (Chang et al., 2016). Therefore, the choice of $PM_{2.5}$ pollution as the air pollution variable is more conclusive. In the robustness check section, we use AQI data from ground-based monitoring stations of the Chinese Ministry of Environmental Protection as replacement air pollution indicator data to test the robustness of the regression results.

(2) Household commercial health insurance participation behaviour (*CHI*, *CHIE*)

The household commercial health insurance participation behaviour studied in this paper is divided into two types, namely, whether the household has commercial health insurance (CHI), and the extent of household commercial health insurance participation (CHIE). CHI is a dummy variable with sample data from the 2019 CHFS, and CHI is 1 if a household member has purchased commercial health insurance and 0 if no household member has purchased commercial health insurance. CHIE is defined as the proportion of premium expenditure on commercial health insurance by household members to total household income in the previous year.

(3) Residents' concern

Based on the summary and analysis of the literature review on residents' concern, we selected the following potential channels as residents' concern: pollution reporting, protective behaviors, and healthy depreciation.

Pollution reporting generally appears before the occurrence of risk, with the aim of reducing the probability of risk occurrence. Based on the air pollution study from a pollution reporting perspective (Sun et al., 2021b; 2021a), we use the reporting of environmental pollution by residents in each region in 2018 as the pollution reporting variable, which includes the total number of reports (reports), WeChat channel reports (WeChat) and Internet channel reports (web); Protective behaviors generally appear in the process of risk occurrence, aiming to reduce the harm caused by the risk. Based on the air pollution study from a defensive investment perspective (Ito and Zhang, 2020), we use the defensive investment behaviors of Chinese household residents on respirable dust and haze in 2018 as protective behaviors (PB) variable, such as purchasing air purifiers, masks, green plants, and fresh air systems, etc., with PB taking the value of 1 if they have protective behaviors and 0 otherwise.; Healthy depreciation is the loss of health capital after the risk occurs. Based on studies of the effects of air pollution on physical and mental health (Zheng et al.,

TABLE 1 Variable definitions.

Variable name	Variable description
CHI	Whether family members purchased commercial health insurance in the last year
CHIE	Percentage of total household income spent on commercial health insurance premiums in the last year
$PM_{2.5}$	$PM_{2.5}$ data represent air pollution status
AQI	Air quality index
TI	Annual frequency of thermal inversions in residential areas in the last year
age	Age of household head
edu	Education level of household head
gender	Gender of household head
marry	Marital status of household head
health	Physical condition of household head (self-assessment)
SI	Household head's participation in social insurance
risk	Risk attitude of household head
job	Unemployment of household head
hospital	Whether the household head has been hospitalised in the last year
internet	Whether the household head has a mobile phone with Internet access
income	Total household income in the last year
asset	Total household assets in the last year
consump	Total household consumption in the last year
debt	Whether the household had any debts in the last year
card	Whether the household has credit cards
rural	Area in which the household lives
old	Number of people aged 60 and over in the household
kid	Number of people aged 14 and under in the household

2015; Liu et al., 2017; Chen et al., 2018; Zhang et al., 2018), We use whether Chinese household residents had medical expenditures in 2018 as a healthy depreciation (HD) variable, with HD taking the value of 1 if they had medical expenditures and 0 otherwise.

(4) Control variable

Appropriate control variables are added to obtain better estimation results and to solve the problem of omitted variables. Household participation behaviour in commercial health insurance is influenced by a wide range of factors, so we referred to the results of related studies (Zietz, 2003; Hussels et al., 2005; Outreville, 2013) and combined the characteristics of the sample data to set two sets of control variables, one for household characteristics and the other for the personal characteristics of the household head.

The control variables for household characteristics include total household income, total household assets, total household consumption, total household debt, credit card, whether the household residence is in a rural area, the proportion of the household population aged 60 or above, and the proportion of the household population aged 14 or below. The Control variables for the personal characteristics of the household head include age, health, hospital behaviour, gender, marital status, educational attainment, social insurance participation, risk attitude, unemployment and internet.

(5) Instrumental variable (*TI*)

The instrumental variable should be highly correlated with the independent variable and should not directly affect the dependent variable. On the basis of satisfying this condition, thermal inversions can solve the air pollution endogenous problem to some extent (Fu and Gu, 2017; Fu et al., 2018; Chen et al., 2020). We therefore chose to use thermal inversion (TI) as the instrumental variable to address the endogenous issue in conjunction with the household sample data characteristics.

The thermal inversion data were obtained from NASA's MERRA-2 product, dataset code M2I6NPANA. The raw data were global atmospheric temperatures at 42 barometric levels, collected at a frequency of 6 h/time, and we used ArcGIS10.8 to extract the 2018 data based on the administrative area of prefecture-level cities. The percentage of days in a year when

thermal inversions occur in prefecture-level municipalities is the instrumental variable.

Table 1 describes the definition of each variable.

4.2 Model construction

The first question discussed is whether air pollution affects household participation in commercial health insurance, i.e., whether air pollution motivates households to purchase commercial health insurance or if it acts as a disincentive. There are only two states of household participation in commercial health insurance, namely, insured and non-insured states, which are dummy variables. The Probit model is therefore chosen to estimate the effect of air pollution on whether households take out commercial health insurance, while the thermal inversion instrumental variable is introduced to control for endogeneity in the model, resulting in the construction of the following IV-Probit model:

$$pollution_i = \tau_0 + \tau_1 Z_i + \tau_3 X_i + \varepsilon_i \quad (2)$$

$$Pr(CHI_i = 1) = \phi(\alpha_0 + \alpha_1 Pollution_i + \alpha_2 X_i + \varepsilon_i) \quad (3)$$

Where i denotes the ith household; CHI_i represents whether anyone in the household has commercial health insurance; $pollution_i$ is air pollution, denoted by $PM_{2.5}$; Z_i indicates the instrumental variable; X_i stands for the control variable; ε_i signifies the residual term; and α_1 is the coefficient to be estimated.

The second question discussed is the extent to which air pollution affects household participation in commercial health insurance., i.e., whether air pollution positively or negatively affects household investment in commercial health insurance as a proportion of total income. The number of households with commercial health insurance in the data sample selected for this paper is small (i.e., the ratio of commercial health insurance premium expenditure to total income is truncated), and the thermal inversion instrumental variable is introduced to control for endogeneity in the model; therefore, the IV-Tobit model is chosen to estimate the impact of air pollution on household participation in commercial health insurance by constructing the following IV-Tobit econometric model:

$$pollution_i = \vartheta_0 + \vartheta_1 Z_i + \vartheta_3 X_i + \varepsilon_i \quad (4)$$

$$CHIE_i^* = \beta_0 + \beta_1 Pollution_i + \beta_2 X_i + \varepsilon_i \quad (5)$$

$$CHIE_i^* = max(0, CHIE_i^*) \quad (6)$$

Where i denotes the ith household; $CHIE_i$ is the proportion of household members' total income spent on commercial health insurance premiums; $Pollution_i$ represents air pollution, denoted by $PM_{2.5}$; Z_i indicates the instrumental variable; X_i stands for the control variable; ε_i signifies the residual term; and β_1 is the coefficient to be estimated.

The third question discussed is a mechanistic test of air pollution and household commercial health insurance participation behaviour, i.e., whether residents' concern is a channel through which air pollution affects household commercial health insurance participation behaviour. We draw on previous empirical research approaches to mechanism testing (Alesina and Zhuravskaya, 2011). Based on the IV-Probit and IV-Tobit models we constructed, we added residents' concern as a potential channel variable in the regression process and made mechanism tests and transmission direction judgments based on the changes in the estimated coefficients. When the estimated coefficient of the effect of air pollution becomes smaller after the residents' concern is added as an additional control variable in the benchmark regression, it is judged that residents' concern is a potential channel for air pollution to affect household commercial health insurance participation behaviour and has a positive transmission effect. Conversely, when the estimated coefficient of the effect of air pollution becomes larger, then residents' concern is judged to be a potential channel through which air pollution affects household commercial health insurance participation behaviour, but with a negative transmission effect (The models are not repeated here)

TABLE 2 Descriptive statistics.

Statistic	Observations	Mean	St. Dev	Min	Max
CHI	32,645	0.034	0.182	0	1
CHIE	32,645	0.002	0.020	0	0.955
$PM_{2.5}$	32,645	35.240	10.763	2.537	62.817
AQI	32,645	70.248	18.871	33.449	114.124
TI	32,645	0.706	0.209	0.041	0.997
age	32,645	56.419	13.750	17.000	101.000
edu	32,645	0.147	0.354	0	1
gender	32,645	0.753	0.431	0	1
marry	32,645	0.970	0.169	0	1
health	32,645	0.395	0.489	0	1
SI	32,645	0.941	0.236	0	1
risk	32,645	0.052	0.222	0	1
job	32,645	0.353	0.478	0	1
hospital	32,645	0.170	0.375	0	1
internet	32,645	0.701	0.458	0	1
income	32,645	86,597.500	1.97e+05	0	1.21e+07
asset	32,645	1.15e+06	1.25e+07	0	2.10e+09
consump	32,645	82,821.063	9.43e+05	1,356.000	1.70e+08
debt	32,645	0.523	0.499	0	1
card	32,645	0.033	0.179	0	1
rural	32,645	0.347	0.476	0	1
old	32,645	0.885	0.893	0	4
kid	32,645	0.430	0.747	0	7

5 Results and discussion

5.1 Descriptive statistics

Table 2 reports the descriptive statistics of the matched sample data.

TABLE 3 Regression results.

	1)	2)	3)	4)
	CHI	***CHI***	***CHIE***	***CHIE***
$PM_{2.5}$	0.274***	0.560***	0.0495***	0.115***
	(0.049)	(0.117)	(0.009)	(0.024)
age	0.0389***	0.0387***	0.0102***	0.0101***
	(0.010)	(0.010)	(0.002)	(0.002)
age2	−0.000521***	−0.000521***	−0.000130***	−0.000130***
	(0.000)	(0.000)	(0.000)	(0.000)
edu	0.196***	0.186***	0.0300***	0.0280***
	(0.038)	(0.038)	(0.007)	(0.007)
gender	−0.265***	−0.260***	−0.0449***	−0.0439***
	(0.034)	(0.034)	(0.007)	(0.007)
marry	−0.0497	−0.0594	−0.00454	−0.0068
	(0.083)	(0.082)	(0.015)	(0.015)
health	0.0476	0.0443	0.0146**	0.0139**
	(0.032)	(0.032)	(0.006)	(0.006)
SI	0.000885	0.00473	0.00025	0.0012
	(0.070)	(0.069)	(0.013)	(0.013)
risk	0.0835*	0.0923*	0.0124	0.0145
	(0.051)	(0.050)	(0.009)	(0.009)
job	−0.134***	−0.127***	−0.0182**	−0.0168*
	(0.047)	(0.047)	(0.009)	(0.009)
hospital	−0.00049	0.00403	0.00434	0.00541
	(0.049)	(0.049)	(0.010)	(0.010)
internet	0.354***	0.360***	0.0716***	0.0732***
	(0.068)	(0.068)	(0.015)	(0.015)
asset	0.0754***	0.0707***	0.0155***	0.0145***
	(0.013)	(0.014)	(0.003)	(0.003)
income	0.122***	0.121***	0.00929***	0.00905***
	(0.016)	(0.016)	(0.002)	(0.002)
consump	0.0964***	0.102***	0.0176***	0.0191***
	(0.023)	(0.023)	(0.005)	(0.005)
debt	0.00729	0.0244	0.00069	0.00456
	(0.033)	(0.033)	(0.006)	(0.006)
card	0.359***	0.357***	0.0641***	0.0640***
	(0.055)	(0.055)	(0.011)	(0.011)
rural	−0.149***	−0.128***	−0.0302***	−0.0255***
	(0.043)	(0.044)	(0.009)	(0.009)
old	−0.0848***	−0.0874***	−0.0166***	−0.0172***

(Continued on following page)

TABLE 3 (*Continued*) **Regression results.**

	1)	2)	3)	4)
	(0.025)	(0.025)	(0.005)	(0.005)
kid	−0.0234	−0.0199	−0.00526	−0.0045
	(0.021)	(0.021)	(0.004)	(0.004)
Wald test		6.88***		10.16***
Pseudo R2	0.180		0.261	
F-value		319.73		319.73
Observations	32,645	32,645	32,645	32,645

Household clustering robust standard errors in brackets; ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

5.2 Analysis of main empirical results

First, we need to test the endogeneity of the regression model as a prerequisite for the effective use of instrumental variables. Table 3 reports the Wald tests for the IV-Probit and IV-Tobit models, both of which are significant at the 1% level, indicating that the dependent variables are endogenous and that instrumental variables should be used. In addition, the one-stage F-values for both regression models are greater than 10, indicating that the instrumental variable passes the Cragg-Donald test, rejecting the weak instrumental variable hypothesis, and suggesting that thermal inversion is a qualified instrumental variable.

Table 3 reports the results of our regressions. Columns 1) and 3) show the regression results for the Probit and Tobit models, while columns 2) and 4) show the regression results for the IV-Probit and IV-Tobit models. Comparing these, we find that the regression results with the addition of instrumental variables are still significant and that the regression coefficients are larger, suggesting that the Probit and Tobit models are endogenous and thus underestimate the effect of air pollution on household participation in commercial health insurance. Therefore, we chooses to use the regression results of the IV-Probit and IV-Tobit models to estimate the marginal effects. The IV-Probit model estimates the effect of air pollution on the likelihood of household participation in commercial health insurance with a regression coefficient of 0.358 and a marginal effect of 0.0149, which indicates that for every 1% increase in $PM_{2.5}$ concentration, the likelihood of household participation in purchasing commercial health insurance rises by 1.49%. The IV-Tobit model estimates the effect of air pollution on household participation in commercial health insurance with a regression coefficient of 0.115 and a marginal effect of 0.1148, which indicates that for every 1% increase in $PM_{2.5}$ concentration, household expenditure on commercial health insurance as a proportion of total income rises by 11.48%. Our estimates are consistent with the results of Jia and Yan (2022) on the relationship between air pollution and household commercial health insurance. So, air pollution increased the likelihood of household participation in purchasing commercial health insurance and household expenditure on commercial health insurance as a proportion of total income, verifying Hypothesis 1a.

The regression results of the control variables show that total household income, total household assets and total household consumption have a positive impact on household participation in commercial health insurance, and that the likelihood of purchasing commercial health insurance increases as total household income increases. Tian and Dong (2022) study found that in terms of the financial status of the family, the total consumption of the household has a positive and significant effect on the breadth and depth of health insurance. This is consistent with our finings. Credit card ownership has a positive impact on household commercial health insurance participation behavior. Living in a rural area has a negative impact on household participation in commercial health insurance, probably because commercial health insurance is less widespread in rural areas and the income and education level of rural residents are lower than those of urban residents. The proportion of the population that is elderly has a negative impact on household participation in commercial health insurance, suggesting that as China ages, the demand for commercial health insurance decreases.

The regression results for the age, quadratic age, unemployment, education, gender and internet of the household head are significant. The regression results are positive for age and negative for the quadratic age, indicating that the household's need for commercial health insurance changes from increasing to decreasing as the age of the household head increases. The regression coefficients for educational attainment indicate that the educational attainment of the household head has a positive effect on household participation in commercial health insurance. The regression coefficients for gender show that the male head of household reduce the household's commercial health insurance participation behaviour. The regression coefficients for unemployment show that the unemployment of household head reduce the household's commercial health insurance participation behaviour. The regression coefficients for internet indicate that the use of the Internet by the household head has a positive effect on household participation in commercial health insurance.

6 Mechanisms

The Residents' concern is an important channel linking air pollution to commercial health Insurance's sustainable development. The residents' concern in this paper include pollution reporting, protective behaviors, and healthy

TABLE 4 Results of the mechanism test with CHI.

	1)	2)	3)	4)	5)	6)
		reports	***Wechat***	***web***	***PB***	***HD***
	CHI	***CHI***	***CHI***	***CHI***	***CHI***	***CHI***
$PM_{2.5}$	0.560***	0.565***	0.644***	0.627***	0.512***	0.555***
	(0.117)	(0.113)	(0.123)	(0.127)	(0.119)	(0.118)
concerns		−0.027*	−0.00851**	−0.0227**	0.120***	0.0829**
		(0.021)	(0.022)	(0.027)	(0.038)	(0.034)
Wald chi2	6.88***	8.62***	13.07***	12.90***	5.79**	6.63***
F-value	319.73	691.30	737.47	1,057.28	313.21	304.62
Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	32,645	32,645	32,645	32,645	32,645	32,645

Household clustering robust standard errors in brackets; ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

depreciation. Below we explore three potential channels through which air pollution might affect the commercial health insurance's sustainable development: pollution reporting, protective behaviors, and healthy depreciation.

Table 4 reports the results of the mechanism test with CHI as the dependent variable. Column 1) is the benchmark regression and reports the results of the regression of air pollution on whether households participate in purchasing commercial health insurance. Columns (2)–(6) show the regression results for total number of reports, WeChat channel reports, Internet channel reports, protective behaviors and healthy depreciation as additional control variables, respectively. Comparing the regression results in columns (2)–(6) with the benchmark regression results, respectively, we found that the regression coefficients all became larger or smaller and were significant. This indicates that residents' concern is a potential channel through which air pollution affects household participation in the purchase of commercial health insurance.

Comparing the regression results of column 2), column 3) and column 4) with the benchmark regression results, we found that the regression coefficients were significantly higher. The regression coefficient of $PM_{2.5}$ in the benchmark regression is 0.560, while the regression coefficients of column 2), column 3) and column 4) are 0.565, 0.644 and 0.627, respectively, which are all significant. This indicates that the total number of reports, WeChat channel reports and Internet channel reports play a negative transmission role of air pollution affecting household participation in the purchase of commercial health insurance.

Comparing the regression results of column 5) and column 6) with the benchmark regression results, we found that the regression coefficients were significantly lower. The regression coefficient of $PM_{2.5}$ in the benchmark regression is 0.560, while the regression coefficients of column 5) and column 6) are 0.512 and 0.555, respectively, which are both significant. This suggests that protective behaviors and healthy depreciation play a positive transmission role of air pollution affecting household participation in the purchase of commercial health insurance. The above results verify hypothesis 1b.

Table 5 reports the results of the mechanism test with CHIE as the dependent variable. The regression results in Table 5 are similar to Table 4, which indicates that residents' concern is a potential channel through which air pollution affects the extent of household commercial health insurance participation.

The column 2), column 3) and column 4) show significantly higher regression coefficients compared to the benchmark regression. The regression coefficient of the benchmark regression is 0.115, while the regression coefficients of column 2), column 3) and column 4) are 0.124, 0.130 and 0.127, all of which are highly significant. This indicates that the total number of reports, We Chat channel reports and Internet channel reports play a negative transmission role of air pollution affecting the extent of household commercial health insurance participation.

The regression coefficients in columns 5) and 6) are significantly higher compared to the benchmark regression. The regression coefficient of the benchmark regression is 0.115, while the regression coefficients of columns 5) and 6) are 0.107 and 0.114 and are highly significant. This indicates the positive transmission effect of protective behaviors and healthy depreciation on the effect of air pollution on the extent of household commercial health insurance participation. The above results verify hypothesis 2a.

7 Robustness test

7.1 Substitution of independent variables

To test the robustness of the empirical regression results, we chose to use AQI, which can reflect the level of air pollution, instead of the original independent variables. Data on AQI was obtained from ground-based monitoring stations in China. The regression results after replacing the independent variables are reported in Table 6. Panel A shows the regression results of the IV-Probit model. It can be seen that the regression coefficients of AQI indicator is

TABLE 5 Results of the mechanism test with CHIE.

	1)	2)	3)	4)	5)	6)
		reports	***Wechat***	***web***	***PB***	***HD***
	CHIE	***CHIE***	***CHIE***	***CHIE***	***CHIE***	***CHIE***
$PM_{2.5}$	0.115***	0.124***	0.130***	0.127***	0.107***	0.114***
	(0.024)	(0.023)	(0.025)	(0.026)	(0.024)	(0.024)
concerns		−0.00827**	−0.0048**	−0.00835**	0.0168***	0.0153**
		(0.004)	(0.004)	(0.005)	(0.007)	(0.007)
Wald chi2	10.16***	10.87***	15.84***	15.42***	9.03***	9.87***
F-value	319.73	691.30	737.47	1,057.28	313.21	304.62
Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	32,645	32,645	32,645	32,645	32,645	32,645

Household clustering robust standard errors in brackets; ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

TABLE 6 Regression results after replacing the independent variables.

	1)	2)	3)	4)	5)	6)
		reports	***Wechat***	***web***	***PB***	***HD***
Panel A	***CHI***	***CHI***	***CHI***	***CHI***	***CHI***	***CHI***
AQI	0.470***	0.506***	0.569***	0.541***	0.429***	0.466***
	(0.105)	(0.105)	(0.111)	(0.113)	(0.107)	(0.106)
concerns		0.0315**	0.0541***	0.0437**	0.131***	0.0769**
		(0.015)	(0.016)	(0.018)	(0.037)	(0.034)
Wald chi2	4.29**	6.40***	9.48***	9.91***	3.98**	4.21**
F-value	600.27	603.46	674.20	868.68	585.59	572.27
Panel B	***CHIE***	***CHIE***	***CHIE***	***CHIE***	***CHIE***	***CHIE***
AQI	0.0971***	0.102***	0.114***	0.109***	0.0907***	0.0964***
	(0.021)	(0.021)	(0.022)	(0.022)	(0.021)	(0.021)
concerns		0.00361*	0.00783**	0.00509*	0.0189***	0.0140**
		(0.003)	(0.003)	(0.003)	(0.007)	(0.007)
Wald chi2	6.62**	8.38***	11.65***	11.80***	6.28**	6.54**
F-value	600.27	603.46	674.20	868.68	585.59	572.27
Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	32,645	32,645	32,645	32,645	32,645	32,645

Household clustering robust standard errors in brackets; ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

close to the regression coefficients of the original independent variables and is significant at the 1% level. Panel B presents the regression results of the IV-Tobit model. It can be seen that the regression coefficients of AQI indicators is close to the regression coefficients of the original independent variables and is significant at the 1% level. The above results prove that the regression results are robust.

7.2 Excluding the effects of natural selection bias

As some residents are more sensitive to air pollution or more aware of risk prevention, they may choose to migrate to cities with good air quality, which may make the regression results biased and produce a natural selection bias. Therefore, we excluded the sample

TABLE 7 Regression results of excluding the migrated sample.

	1)	3)	4)	5)	6)	7)
		reports	***Wechat***	***web***	***PB***	***HD***
Panel A	***CHI***	***CHI***	***CHI***	***CHI***	***CHI***	***CHI***
$PM_{2.5}$	0.556***	0.558***	0.641***	0.622***	0.507***	0.551***
	(0.120)	(0.116)	(0.126)	(0.130)	(0.122)	(0.120)
concerns		−0.0291*	−0.00736**	−0.0209*	0.126***	0.0908***
		(0.021)	(0.023)	(0.028)	(0.039)	(0.035)
Wald chi2	5.73**	6.79***	11.27***	11.01***	4.71**	5.50**
F-value	308.41	672.55	719.62	1,028.60	301.43	293.88
Panel B	***CHIE***	***CHIE***	***CHIE***	***CHIE***	***CHIE***	***CHIE***
$PM_{2.5}$	0.1139***	0.122***	0.128***	0.126***	0.106***	0.1130***
	(0.024)	(0.025)	(0.026)	(0.027)	(0.024)	(0.024)
concerns		−0.00889**	−0.0047	−0.00797	0.0179**	0.0165**
		(0.004)	(0.004)	(0.005)	(0.008)	(0.007)
Wald chi2	8.37***	8.27***	13.09***	12.73***	7.32***	8.10***
F-value	308.41	672.55	719.62	1,028.60	301.43	293.88
Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31,600	31,600	31,600	31,600	31,600	31,600

Household clustering robust standard errors in brackets; ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

of households with migration behaviors. The migration rate of the valid sample was 3.21%, the number of samples with migration behaviors was 1,045, and the overall valid sample was 32,645, leaving 31,600 after processing. This indicates that the migration rate of Chinese residents is not high. Table 7 reports the results of the regression excluding the migrated sample. Panel A and panel B show the regression results for the IV-Probit and IV-Tobit models, respectively, which are consistent with our benchmark regression results, indicating the robustness of the regression results.

8 Conclusion

Due to the negative physical and psychological effects of air pollution on residents, the burden of medical expenses increases as a consequence, and the wellbeing of residents is negatively impacted. In order to combat the effects of these problems, in addition to tackling environmental pollution, commercial health insurance can help to alleviate the pressure on residents' healthcare costs. It provides an effective way to reduce the financial burden of healthcare associated with air pollution and can help to improve family wellbeing. It is therefore important to study the relationship and mechanism between $PM_{2.5}$ and commercial health insurance participation, not only to help residents understand the negative effects of air pollution so that countermeasure policies can be formulated to improve household welfare, but also to provide a reference for the sustainable development of commercial health insurance for insurance companies. Using data from van et al., 2010 and through matching it with $PM_{2.5}$ data by city, we investigated the impact and mechanisms of air pollution on household commercial health insurance participation behaviors using the IV-Probit and the IV-Tobit models. The final conclusions obtained are as follows.

The marginal effect of $PM_{2.5}$ pollution on the likelihood of household participation in commercial health insurance is that for every 1% increase in $PM_{2.5}$ concentration, the likelihood of a household purchasing commercial health insurance increases by 1.49%. The marginal effect of $PM_{2.5}$ pollution on household participation in commercial health insurance coverage is that for every 1% increase in $PM_{2.5}$ concentration, the proportion of total household income spent on commercial health insurance increases by 11.48%.

Residents' concern is an important channel linking air pollution to Household commercial health insurance participation behaviors, where pollution reporting plays a negative transmission role, protective behaviors play a positive transmission role, and healthy depreciation plays a positive transmission role.

The above findings pass the two robustness tests of replacing the independent variables and excluding selectivity bias, proving the credibility of the regression results and conclusions. We therefore make the following policy recommendations in conjunction with the empirical findings. In order to improve the health and welfare status of the population, the cooperation between social insurance and commercial health insurance should be strengthened in China, and publicity and advisory services on commercial health insurance should be provided to the population so as to increase their awareness of risk prevention and sensitivity to $PM_{2.5}$ pollution

and thus encourage their active participation in commercial health insurance. Insurance companies should innovate according to different influencing factors, such as air pollution level, residents' background, residents' education level, and different mechanisms, such as pollution reporting, protective behaviors and health depreciation, in order to ensure the sustainable development of commercial health insurance, relieve the pressure of medical expenses and improve the health of residents.

We were limited by cross-sectional data to examine the relationship between air pollution and commercial health insurance over time. In addition, we used a single type of air pollution and did not comprehensively examine the impact of air pollution on commercial health insurance. It is hoped that in future studies, panel data can be constructed and comprehensive air pollution data can be collected for the study, making the results more accurate.

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

TR: formal analysis, investigation, and validation. QZ: conceptualization, methodology, and writing—original draft and editing. WW: mechanisms and writing—revising and editing. XD: conceptualization and writing—review and editing. All authors contributed to the manuscript and approved the submitted version.

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Conflict of interest

Author TR was employed by the company Huatai Insurance Agency and Consultant Service Ltd. QZ China Export and Credit Insurance Corporation.

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Evolutionary game and simulation analysis on quality supervision of low-carbon renovation of high-carbon emission enterprises under the reward and punishment mechanism

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From the perspective of multi-stakeholders, considering the rent-seeking phenomenon existing in the inspection and acceptance of low-carbon renovation under the government's reward and punishment mechanism, this paper constructs a tripartite evolutionary game model of the government, third-party testing institutions, and high-carbon emission enterprises, analyzes the stability of the evolutionary strategies of all parties involved, and tests the influence of the reward and punishment mechanism, rent-seeking cost, and the cost difference between high carbon and low carbon on the choice of tripartite strategies through simulation. Finally, the stability of the equilibrium point in the tripartite game system is verified. The results show that 1 the government's increase in the reward and punishment mechanism will promote the low-carbon renovation of high-carbon emission enterprises and the refusal to rent-seeking behavior choices, but the increase in incentives will weaken the government's supervision; 2 the reward and punishment mechanism set by the government must meet the condition that the sum of the strength of the reward and punishment mechanism for each party is greater than its speculative income, so as to ensure the quality of low-carbon renovation of high-carbon emission enterprises; 3 the greater the rent-seeking cost paid by high-carbon emission enterprises, the more conducive it is to avoiding the unqualified low-carbon renovation of high-carbon emission enterprises; and 4 under the premise of certain sales revenue, the greater the cost difference between low-carbon production and high-carbon production, the lower the willingness of enterprises to low-carbon renovation. Therefore, reducing the production cost difference is an effective way to promote the low-carbon renovation of high-carbon emission enterprises.

KEYWORDS

low-carbon renovation, quality supervision, rent-seeking, tripartite evolutionary game, reward and punishment mechanism

1 Introduction

According to the China's Listed Companies Carbon Emissions List (2022) released in September 2022, China's total carbon emissions in 2021 exceeded 10.3 billion tons, accounting for about 27% of the total global carbon emissions. The 100 listed companies, total carbon emissions of about 5.1 billion tons, account for about 49.5% of the total. The total carbon emissions of the top 10 enterprises are more than 150 million tons, accounting for about 44% of the total emissions. The total emissions of these traditional high-carbon emission enterprises such as electricity, petrochemical, and coal are almost close to the total emissions of all the remaining enterprises. It can be seen that the low-carbon renovation of traditional high-carbon emission enterprises is the key path to realize the green and low-carbon renovation of the economy (Yunchao et al., 2022), which is the requirement of high-quality economic development and the proper meaning of China's participation in global governance. Since 2022, Chinese governments have promulgated a series of relevant policies and regulations to encourage low-carbon renovation of traditional industries and support environmentally sustainable development. For example, in December 2022, the Beijing State-owned Assets Supervision and Administration Commission issued the "action plan for carbon peaking of municipal enterprises" proposing the low-carbon renovation of high-carbon emission enterprises. This is an important way to transform the industrial structure and accelerate the low-carbon cycle transformation of own property and industrial parks. It is required to focus on public buildings such as office buildings, hotels, and commercial supermarkets to carry out energy efficiency assessments and take the lead in promoting low-carbon renovation of existing buildings that meet the conditions. As an auxiliary force of the government in the professional field, third-party testing institutions are prone to rent-seeking behavior driven by interests. For example, in November 2022, the Shanghai Municipal Government notified four institutions in Shanghai of fraud in activities related to environmental monitoring services. At the same time, the Anhui Provincial Department of Ecology and Environment notified eight typical cases of third-party environmental testing agencies falsifying detection data in Anhui Province.

However, the overall atmosphere of low-carbon renovation of China's high-carbon emission enterprises has not yet been formed (Tingting and Shuhui, 2022). From the perspective of the production side of carbon emissions, traditional high-carbon emission enterprises have profit-seeking motives (Guo and Huang, 2021). Focusing on short-term interest balance, low-carbon renovation is insufficient. In the absence of government guidance, they usually choose to maintain high-carbon production strategies to save total production costs. From the perspective of government supervision, in order to encourage high-carbon emission enterprises to carry out low-carbon renovation, the government will formulate a reward and punishment mechanism for low-carbon renovation of high-carbon emission enterprises to cultivate and guide high-carbon emission enterprises to implement low-carbon renovation. However, in reality, due to the lack of government supervision in the professional field, the reward and punishment mechanism is difficult to fundamentally implement (Wang et al., 2022; Ziming et al., 2022); from the perspective of professional testing guarantee, the third-party testing institutions, as an auxiliary force to make up for the lack of government supervision ability in the professional field (Bin et al., 2020), become the judge of whether the high-carbon emission enterprises complete the low-carbon renovation. Driven by the interests, the third-party testing institutions have the risk of agreeing to rent-seeking (Liu et al., 2020; Lv et al., 2022), resulting in the low-carbon renovation quality of high-carbon emission enterprises failing to meet the government's requirements. Through the literature review and existing policy review, it is found that most of the low-carbon renovation policy documents on existing facilities are issued in 2022. However, the existing research mainly focuses on the evaluation of low-carbon renovation and the research on low-carbon emission reduction strategies of enterprises (Qu et al., 2021; Bai and Zhang, 2022; Jiang et al., 2020b; Dong et al., 2021). The research on the low-carbon renovation of high-carbon emission enterprises has only begun to receive attention recently, and related research has begun to expand. In order to fill this research gap, this paper explores the quality supervision of low-carbon renovation of high-carbon emission enterprises under the government reward and punishment mechanism, which has a guiding significance for

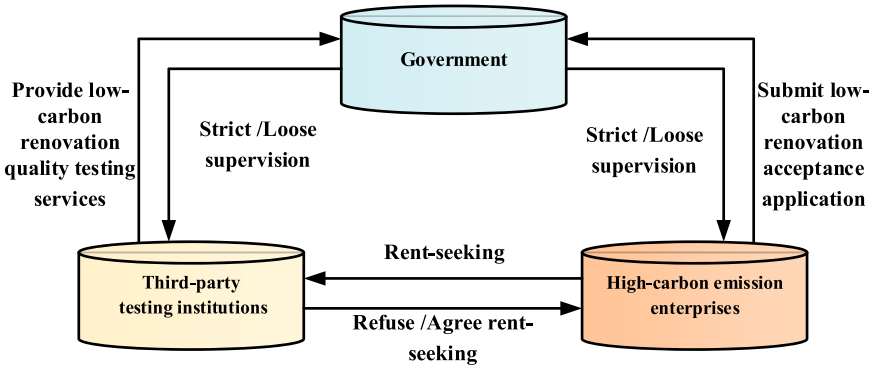

FIGURE 1
Logical relationship diagram of the tripartite evolutionary game model.

improving the quality of low-carbon renovation of high-carbon emission enterprises.

Through the aforementioned analysis, it can be seen that there is information asymmetry among the government, high-carbon emission enterprises, and third-party testing institutions, which is a non-cooperative game relationship. Compared with the traditional game theory, the evolutionary game is based on the bounded rationality of decision makers and does not require complete information conditions (ShengYuan et al., 2022). Evolutionary game analysis with multi-agent participation is more helpful to reveal complex problems (Feng et al., 2020; Xie et al., 2022). Studies have confirmed the effectiveness of evolutionary games in the study of quality supervision. Therefore, the evolutionary game is an effective method to study the dynamic change of multi-agent strategy under bounded rationality, which is suitable for the quality supervision of low-carbon renovation studied in this paper. In this paper, the evolutionary game between the government, high-carbon emission enterprises, and third-party testing institutions can be expressed as follows: in order to promote the low-carbon renovation of high-carbon emission enterprises, the government formulates policies on the reward and punishment mechanism to supervise the quality of low-carbon renovation. Based on the maximization of benefits, enterprises and third-party testing institutions will change with the intensity and cost of rewards and punishments, and behavioral strategies will change dynamically.

This paper answers the following key questions:

1) How does the government's reward and punishment mechanism affect the strategic choice of high-carbon emission enterprises and third-party testing institutions?
2) What kind of reward and punishment mechanism can ensure the quality of low-carbon renovation of high-carbon emission enterprises?
3) How does rent-seeking behavior affect the strategic choice of high-carbon emission enterprises and third-party testing institutions?
4) How should the government respond effectively to the impact of the difference between the cost of low-carbon retrofit and the cost of high-carbon production on the strategic choices of high-carbon emission enterprises?

The remainder of the paper is organized as follows. Section 2 reviews related research; Section 3 proposes research hypotheses and constructs an evolutionary game model; Section 4 analyzes the stability of the evolutionary game strategy; Section 5 analyzes the influence of key variables on game equilibrium; and Section 6 provides conclusion, suggestions, and limitations.

2 Literature review

At present, there are two different research ideas on the low-carbon renovation of enterprises at home and abroad: to study the impact of low-carbon renovation behavior on the behavior strategies of all parties on low-carbon development from the perspective of stakeholders and from the perspective of empirical research to study the impact of low-carbon business transformation factors. Based on the first research idea, this paper explores the quality supervision of low-carbon renovation of high-carbon emission enterprises.

The research on the behavior strategy of low-carbon renovation of enterprises mainly focuses on the relationship between the government and enterprises, and the research based on game theory is particularly extensive. In the study of government policies on low-carbon renovation of enterprises (Du et al., 2021; Caijiang et al., 2022; Chen et al., 2022; Huo et al., 2022; Shi et al., 2022), this study analyzes the impact of government environmental policies on low-carbon renovation of enterprises and puts forward relevant suggestions. Fan et al. (2021) studied the problem of overcapacity in coal enterprises under government environmental supervision and concluded that environmental supervision helped low-carbon production in the coal industry. Wan et al. (2021) and Hu and Wang (2022) believed that the government subsidy mechanism can promote low-carbon development. Gao et al. (2022) proposed that the behavior of enterprises depends on the benefits of green innovation and the losses without green innovation. Li (2022) found that the low-carbon behavior of construction enterprises depends on the construction income and government reward and punishment policies. Such research studies can be used as a reference, but only the two stakeholders of government and enterprises are considered, ignoring the impact of other stakeholders on low-carbon renovation.

In the research of low-carbon renovation of traditional high-carbon emission enterprises, Wang et al. (2020), Li et al. (2022), and Shao xiong et al. (2022) constructed a dynamic game model of the evolution and development of enterprise carbon emission reduction and proposed enterprise carbon emission reduction strategies. Cui (2022), Cui (2019), and Yang et al. (2022) proposed that enterprise innovation is the key for high-carbon emission enterprises to determine the effect of carbon emission reduction. Wang and Zhang (2022) examined the role of the carbon emission trading mechanism in the low-carbon renovation of high-carbon emission enterprises. Qu and Sun (2022) and Suyong et al. (2021) proposed the role of flexible carbon tax policy in promoting energy conservation and emission reduction of high-carbon emission enterprises. Jiang et al. (2020a) and Liu et al. (2022) decomposed the influencing factors of low-carbon renovation of high-carbon emissions and proposed that innovation is crucial to green transformation and development. The research on low-carbon renovation of high-carbon emission enterprises is abundant, but the research direction is mostly transformation strategy and influencing factors, and there is lack of research on quality supervision of low-carbon renovation.

In the field of quality supervision (Xu et al., 2021), the evolutionary game method is applied to the study of inland waterway pollution regulation. He et al. (2021) and Wen et al. (2021) studied the quality supervision of online shopping from the perspective of government regulation by using evolutionary game theory. Yang et al. (2021) built an evolutionary game model of the government, contractors, and the public to study the problem of project quality supervision. Sun et al. (2022) constructed an evolutionary game model based on prospect theory to study carbon emission regulation. Xia et (al. studied the quality control of automobile recalls, emphasizing the supervisory role of public opinion. The aforementioned

TABLE 1 Tripartite mixed game strategy matrix.

Third-party testing institution			Government	
			Strict supervision z	Loose supervision $1-z$
High-carbon emission enterprises	Low-carbon x	Refuse rent-seeking y	$R-c_l+M_e, B+M_d,$ $S-M_g-M_e-M_d$	$R-c_l, B, S$
		Agree rent-seeking $1-y$	$R-c_l+M_e, B-T_p-P_d,$ $S-M_g-M_e+P_d$	$R-c_l, B-T_p, S$
	High-carbon $1-x$	Refuse rent-seeking y	$R-c_h-P_e, B+M_d,$ $P_e-M_d-M_g-T_g$	$R-c_h, B, -T_g-H_p$
		Agree rent-seeking $1-y$	$R-c_h-P_e-B_t, B-T_P-P_d+B_t,$ $P_e+P_d-M_g-T_g$	$R-c_h-B_t, B-T_P+B_t,$ $-T_g-H_p$

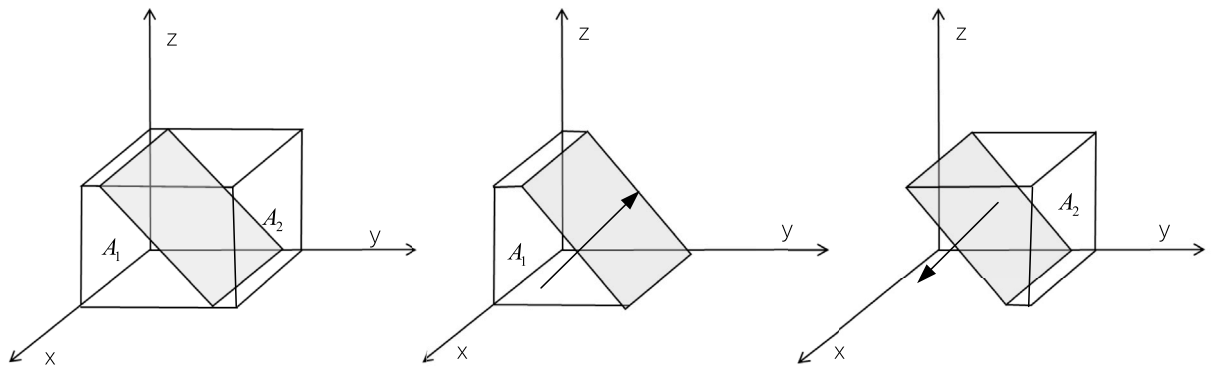

FIGURE 2
Strategy evolution phase diagram of high-carbon emission enterprises.

research shows that the evolutionary game is applicable in the field of quality regulation, but ignores the role of third-party professional institutions in quality regulation. Through the aforementioned research, it can be seen that the evolutionary game has made many explorations in the field of quality supervision, but no research has applied it to the quality supervision of low-carbon renovation.

In summary, many scholars have used evolutionary game methods to study and explore government supervision, low-carbon renovation of enterprises, and quality supervision, which provides a rich research basis for this study. The differences between this article and related literature are mainly as follows:

1) Considering the role of third-party professional institutions in quality supervision, this paper constructs a tripartite evolutionary game model among high-carbon emission enterprises, third-party testing institutions, and governments and studies the three parties within the analytical framework
2) This paper studies the impact of the reward and punishment mechanism on the quality of low-carbon renovation of high-carbon emission enterprises and innovates research perspectives
3) Considering the rent-seeking behavior between third-party testing institutions and enterprises, this paper discusses its impact on the quality supervision of low-carbon renovation

3 Methods and materials

The participation of third-party testing institutions is a guarantee for traditional high-carbon emission enterprises to complete low-carbon renovation according to the standards set by the government. The logical relationship between the three evolutionary game stakeholders of low-carbon renovation quality supervision of high-carbon emission enterprises constructed in this paper is shown in Figure 1.

3.1 Model assumptions

Assumption 1: High-carbon emission enterprise is participant 1, the third-party testing organization is participant 2, and the government is participant 3, the three parties are participants with bounded rationality, and the choice of strategy is stable in the optimal strategy over time.

Assumption 2: High-carbon emission enterprises, third-party testing institutions, and government have two kinds of behavior choices, that is, whether high-carbon emission enterprises carry out low-carbon renovation, α_1 represents low-carbon production,

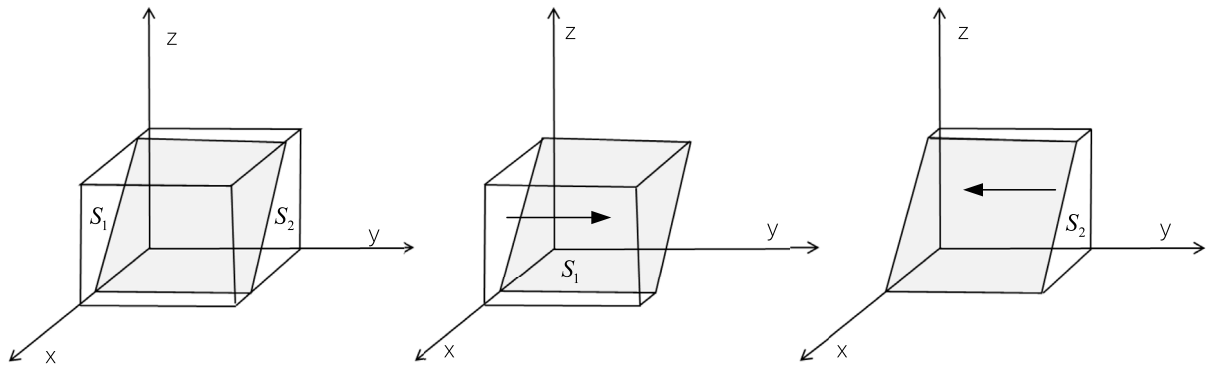

FIGURE 3
Strategy evolution phase diagram of the third-party testing institution.

α_2 represents high-carbon production, and strategic space $\alpha = (\alpha_1, \alpha_2)$; the third-party testing institutions accept rent-seeking behavior, β_1 indicates that it rejects rent-seeking, β_2 indicates that it agrees to rent-seeking, and the strategic space is $\beta = (\beta_1, \beta_2)$; the government adopts strict supervision, γ_1 means strict supervision, γ_2 means loose supervision, and the strategic space is $\gamma = (\gamma_1, \gamma_2)$. We use x, y, and z to represent the choice of low-carbon production, third-party testing institutions to refuse rent-seeking, and the government to take strict regulatory measures, and x, y, $z \in [0, 1]$.

Assumption 3: High-carbon emission enterprises need to be tested by third-party testing institutions. Enterprises that can meet the standards will continue to produce, and enterprises that do not meet the standards will be closed down and unable to continue production and operation. Therefore, all high-carbon emission enterprises must pass the inspection and acceptance of third-party testing institutions to maintain the normal production and operation of enterprises. If high-carbon emission enterprises choose a high-carbon production strategy, in order to maintain production, it will seek rent from a third-party testing agency to meet the requirements of the environmental protection department. If the quality of low-carbon renovation of high-carbon emission enterprises is not so thorough, the quality of renovation has certain defects. The production strategy of enterprises is still high-carbon production. If high-carbon emission enterprises choose a low-carbon production strategy and the low-carbon renovation meets the needs of the government, they will not seek rent from third-party testing institutions.

Assumption 4: The sales revenue of high-carbon emission enterprises is R, the low-carbon production cost is c_l, the high-carbon production cost is c_h, and the low-carbon production cost is higher than the high-carbon production cost ($c_l \geq c_h$). In order to maintain the normal production of enterprises, high-carbon emission enterprises will apply for inspection and acceptance from the third-party testing institutions entrusted by the government, which have been recognized by the government. When the high-carbon emission enterprises maintain the existing production or low-carbon renovation quality cannot fully meet the standards formulated by the government, they will seek rent from the third-party testing institutions. At this time, the enterprise is still high-carbon production, the production cost is c_h, and the rent-seeking cost is B_t

Assumption 5: The test income of third-party testing institutions is B. If the third-party testing institutions have rent-seeking intentions, regardless of whether the high-carbon emission enterprises have rent-seeking needs or not, the third-party testing institutions will have certain non-material costs due to rent-seeking intentions. In fact, the non-material cost of third-party testing institutions is much greater than the material cost of their participation in rent-seeking. Therefore, in this paper, if the third-party testing agency chooses the intention rent-seeking strategy, it will generate rent-seeking costs, and the rent-seeking of the third-party testing agency is T_p.

Assumption 6: When the government adopts a strict regulatory strategy, the regulatory cost is M_g, and the high-carbon emission enterprises do not carry out low-carbon renovation, and the government's punishment is P_e; if completed low-carbon renovation, they will receive government award M_e; the third-party testing institutions accepts the punishment of rent-seeking as P_d, and the reward for refusing rent-seeking is M_d. When the government loosens supervision, the government has no constraints on enterprises and third-party testing institutions.

Assumption 7: The low-carbon renovation of high-carbon emission enterprises is conducive to the improvement of the social environment and government credibility and brings social benefits to the government, that is, S; if high-carbon emission enterprises do not carry out green transformation, in order to maintain the social environment and the credibility of the government, the government needs to carry out environmental remediation of carbon emissions from high-carbon production, the cost is T_g, then the higher authorities will be held accountable to the government, and the loss is H_p.

3.2 Model construction

According to the aforementioned assumptions, a tripartite mixed game strategy matrix of high-carbon emission enterprises, third-party testing institutions, and government is constructed, as shown in Table 1.

4 Model analysis

4.1 Strategy stability analysis of high-carbon emission enterprises

The expected revenue of high-carbon emission enterprises for low-carbon production and high-carbon production is (E_{11}, E_{12}), and the expected revenue is $\bar{E}_1$.

$$\begin{cases} E_{11} = yz(R - c_l + M_e) + y(1-z)(R - c_l) + (1-y)z(R - c_l + M_e) \\ \quad +(1-y)(1-z)(R - c_l), \\ E_{12} = yz(R - c_h - P_e) + y(1-z)(R - c_h) + (1-y)z(R - c_h - P_e - B_t) \\ \quad +(1-y)(1-z)(R - c_h - B_t), \\ \overline{E_1} = xE_{11} + (1-x)E_{12}. \end{cases}$$

Replicated dynamic equation:

$$\begin{aligned} F(x) = dx/dt &= (x - x^2)(E_{11} - E_{12}) \\ &= (x - x^2)[c_h - c_l + B_t - yB_t + z(M_e + P_e)]. \end{aligned}$$

First derivative of x:

$$dF(x)/dx = (1 - 2x)[c_h - c_l + B_t - yB_t + z(M_e + P_e)].$$

Suppose $G(z) = c_h - c_l + B_t - yB_t + z(M_e + P_e)$.

According to the stability theorem of differential equations, the probability of low-carbon production in high-carbon emission enterprises must satisfy $F(x) = 0$ and $\frac{dF(x)}{dx} < 0$, and due to $\frac{\partial G(z)}{\partial z} > 0$, $G(z)$ about y is an increasing function; when $z = \frac{c_l - c_h + yB_t - B_t}{M_e + P_e} = z^*$, $G(z) = 0$, now $\frac{dF(x)}{dx} \equiv 0$, cannot determine the stability strategy; when $z > z^*, G(z) > 0$, now $\frac{dF(x)}{dx}|_{x=0} > 0, x = 0$ is the evolutionary equilibrium strategy point of high-carbon emission enterprises, when enterprises choose low-carbon production; conversely, $x = 1$ is the evolutionary equilibrium strategy point of high-carbon emission enterprises, and enterprises choose high-carbon production. The strategy evolution phase diagram of high-carbon emission enterprises is shown in Figure 2.

It can be seen from the phase diagram that the probability of stable high-carbon production of high-carbon emission enterprises is the volume of V_{A1}, and the probability of stable low-carbon production is the volume of V_{A2}. The calculation method is

$$V_{A1} = \iint_D \frac{c_l - c_h + yB_t - B_t}{M_e + P_e} dydx = \frac{2(c_l - c_h) - B_t}{2(M_e + P_e)},$$

$$V_{A2} = 1 - V_{A1} = \frac{2(c_h - c_l + M_e + P_e) + B_t}{2(M_e + P_e)}.$$

Proposition 1: The probability of high-carbon emission enterprises choosing high-carbon production is negatively related to the rent-seeking cost of high-carbon emission enterprises and the reward and punishment of high-carbon emission enterprises by the government. It is positively correlated with the cost difference between low-carbon production and high-carbon production.

Proof: The difference in the production cost is the key factor for high-carbon emission enterprises to decide whether to carry out low-carbon transformation. If the difference in production costs is lower than the cost of rent-seeking, then there is no need for enterprises to participate in rent-seeking behavior, which has no practical significance. Therefore, the difference in production costs must be greater than its rent-seeking cost. So, we can obtain $c_l - c_h > B_t$. Calculating the first-order partial derivative of each element of the probability V_{A1} of low-carbon production of high-carbon emission enterprises, we can obtain $\frac{\partial V_{A1}}{\partial B_t} < 0, \frac{\partial V_{A1}}{\partial (c_l - c_h)} > 0, \frac{\partial V_{A1}}{\partial M_e} < 0, \frac{\partial V_{A1}}{\partial P_e} < 0$; therefore, the increase in B_t, M_e, P_e and the decrease in $c_l - c_h$ can increase the probability of low-carbon production of high-carbon emission enterprises and promote the green transformation of high-carbon emission enterprises.

Proposition 1 shows that the government can also expand the rewards and punishments of high-carbon emission enterprises, which can effectively promote the willingness of high-carbon emission enterprises to carry out low-carbon renovation. At the same time, it can expand the rent-seeking cost of high-carbon emission enterprises through information construction, production qualification degradation, credit assessment, and other ways and can also promote the low-carbon transformation of high-carbon emission enterprises. In addition, from the perspective of production links, the use of market mechanisms to reduce the cost difference between low-carbon production costs and high-carbon production costs can also effectively promote the low-carbon transformation of high-carbon emission enterprises.

Proposition 2: In the process of evolution, the probability of high-carbon emission enterprises choosing low-carbon production increases with the increase in the probability of third-party testing institutions refusing rent-seeking and the probability of strict supervision by the government.

Proof: When $y < \frac{c_h - c_l + B_t + 2(M_e + P_e)}{B_t}, z > z^*$, we can obtain $G(z) < 0, \frac{dF(x)}{dx}|_{x=0} < 0, x = 1$ as the evolutionary equilibrium strategy point of high-carbon emission enterprises. Conversely, $x = 0$ is the evolutionary equilibrium strategy point of high-carbon emission enterprises. Therefore, with the increase in y, z, the probability x of high-carbon emission enterprises choosing low-carbon production gradually increases.

Proposition 2 shows that the increase in the probability of third-party testing institutions refusing rent-seeking is conducive to the stable strategy of high-carbon emission enterprises choosing low-carbon production. This shows that the government, as a regulatory department, can not only promote the green transformation of high-carbon emission enterprises by improving its own strict supervision measures but also cultivate the social responsibility of third-party testing institutions, improve their fairness, and give full play to their testing and supervision effectiveness, which is conducive to the improvement of the quality of low-carbon renovation.

4.2 Strategy stability analysis of third-party testing institutions

The expected revenue of third-party testing institutions refusing rent-seeking and agreeing rent-seeking is (E_{21}, E_{22}), and the average expected revenue is $\bar{E}_2$.

$$\begin{cases} E_{21} = xz(B + M_d) + x(1-z)B + (1-x)z(B + M_d) + (1-x)(1-z)B, \\ E_{22} = xz\left(B - T_p - P_d\right) + x(1-z)\left(B - T_p\right) \\ \quad +(1-x)z\left(B - T_p - P_d + B_t\right) + (1-x)(1-z)\left(B - T_p + B_t\right), \\ \bar{E}_2 = yE_{21} + (1-y)E_{22}. \end{cases}$$

Replicated dynamic equation:

$$F(y) = dy/dt = (y - y^2)(E_{21} - E_{22}) = (y - y^2)\left[T_p - B_t + xB_t + z(P_d + M_d)\right].$$

First derivative of y: $dF(y)/dy = (1-2y)[T_p - B_t + xB_t + z(P_d + M_d)]$.

Hypothesis 1: $T(z) = T_p - B_t + xB_t + z(P_d + M_d)$

According to the stability theorem of differential equation, the probability of the third-party testing organization choosing to refuse rent-seeking must satisfy $F(y) = 0$ and $\frac{dF(y)}{dy} < 0$, and due to $\frac{\partial T(z)}{\partial z} > 0$, $T(z)$ about z is an increasing function.

When $z = \frac{B_t - xB_t - T_p}{P_d + M_d} = z^*$, $T(z) = 0$, now $\frac{dF(y)}{dy} \equiv 0$, the stability strategy cannot be determined. When $z < z^*$, $T(z) < 0$, now $\frac{dF(y)}{dy}|_{y=0} < 0$, $y = 0$ is the evolutionary equilibrium strategy point, and the third-party testing institutions choose the rent-seeking strategy. On the contrary, $y = 1$ is the evolutionary equilibrium strategy point, and the third-party testing institution chooses to reject the rent-seeking strategy.

The strategy evolution phase diagram of the third-party testing institution is shown in Figure 3.

It can be seen from the phase diagram that the probability of the third-party testing institutions stably choosing rent-seeking is the volume of V_{S1}; the stable refusal rent-seeking probability is the volume of V_{S2}. The calculation is

$$V_{S1} = \iint_D \frac{B_t - xB_t - T_p}{P_d + M_d} dxdy = \frac{B_t - 2T_p}{2(P_d + M_d)},$$

$$V_{S2} = 1 - V_{S1} = \frac{2(P_d + M_d) - B_t + 2T_p}{2(P_d + M_d)}.$$

Proposition 3: The probability of third-party testing institutions choosing rent-seeking is positively correlated with the rent-seeking cost of high-carbon emission enterprises and negatively correlated with their speculative cost and the government's reward and punishment for third-party testing institutions.

Proof: Calculating the first-order partial derivative of each element of the probability V_{S1}, we can obtain $\frac{\partial V_{S1}}{\partial B_t} > 0$, $\frac{\partial V_{S1}}{\partial T_P} < 0$, $\frac{\partial V_{S1}}{\partial (M_d + P_d)} < 0$.Therefore, the probability of third-party testing institutions choosing rent-seeking is positively correlated with the rent-seeking cost of high-carbon emission enterprises; that is, the income B_t obtained by third-party testing institutions when choosing rent-seeking is negatively correlated with the speculative cost T_p and the government's reward and punishment mechanism M_d and P_d when choosing rent-seeking.

Proposition 3 shows that when the third-party testing institutions have large speculative gains, the government should increase rewards and punishments and expand their speculative costs through media publicity, qualification downgrades, and other means, which will help reduce the rent-seeking behavior of third-party testing institutions.

Proposition 4: In the process of evolution, the probability of third-party testing institutions refusing rent-seeking increases with the increase in government strict supervision or the probability of high-carbon emission enterprises choosing low-carbon production.

Proof: when $x < \frac{T_p + z(P_d + M_d)}{B_t}$, $z < z^*$, now $T(z) < 0$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $y = 0$ is the probability of the evolutionary equilibrium strategy; conversely, $y = 1$ is an evolutionary equilibrium strategy. Therefore, the probability of high-carbon emission enterprises choosing low-carbon production or the probability of strict government supervision increases. The probability of third-party testing institutions choosing to refuse rent-seeking increases.

Proposition 4 shows that the choice of third-party testing institutions to refuse rent-seeking strategy is affected by the government's supervision or the choice of low-carbon production strategy by high-carbon emission enterprises. In other words, the government strengthens supervision, and the quality of low-carbon renovation of high-carbon emission enterprises reaches the standard, which can promote third-party testing institutions to refuse rent-seeking. Therefore, in order to ensure the objective fairness of the third-party testing institutions, the government needs strict regulatory measures, while ensuring the quality of low-carbon renovation of high-carbon emission enterprises.

4.3 Strategic stability analysis of government supervision

The expected revenue of the government choosing strict regulation and loose regulation is (E_{31}, E_{32}), and the average expected revenue is $\bar{E}_3$.

$$\begin{cases} E_{31} = xy\left(S - M_e - M_g - M_d\right) + x(1-y)\left(S - M_e - M_g + P_d\right) \\ \qquad +(1-x)y\left(P_e - M_d - M_g - T_g\right) \\ \qquad +(1-x)(1-y)\left(P_e + P_d - M_g - T_g\right), \\ E_{32} = xyS + x(1-y)S + (1-x)y\left(-H_p - T_g\right) \\ \qquad +(1-x)(1-y)\left(-H_p - T_g\right), \\ \bar{E}_3 = zE_{31} + (1-z)E_{32}. \end{cases}$$

Replicated dynamic equation:

$$F(z) = dz/dt = (z - z^2)(E_{31} - E_{32}) = (z - z^2)\left[H_p + P_e + P_d - M_g - x\left(M_e + H_p + P_e\right) - y(P_d + M_d)\right].$$

First derivative of z:

$$dF(z)/dz = (1-2z)\left[H_p + P_e + P_d - M_g - x\left(M_e + H_p + P_e\right) - y(P_d + M_d)\right].$$

Hypothesis 2: $Q(y) = H_p + P_e + P_d - M_g - x(M_e + H_p + P_e) - y(P_d + M_d)$

According to the stability theorem of differential equation, the probability that the government chooses strict supervision to be stable must satisfy $F(z) = 0$ and $\frac{dF(z)}{dz} < 0$, and due to $\frac{\partial Q(y)}{\partial y} < 0$, $Q(y)$ about y is a decrease function.

When $y = \frac{H_p + P_e + P_d - M_g - x(M_e + H_p + P_e)}{P_d + M_d} = y^*$, $Q(y) = 0$, now $\frac{dF(z)}{dz} \equiv 0$, the stability strategy cannot be determined. When $y < y^*$, $Q(y) > 0$, now $\frac{dF(z)}{dz}|_{z=1} < 0$, $z = 1$ is the evolutionary equilibrium strategy point, and the government chooses the strict supervision strategy. On the contrary, $z = 0$ is the evolutionary equilibrium strategy point, and the government chooses the loose

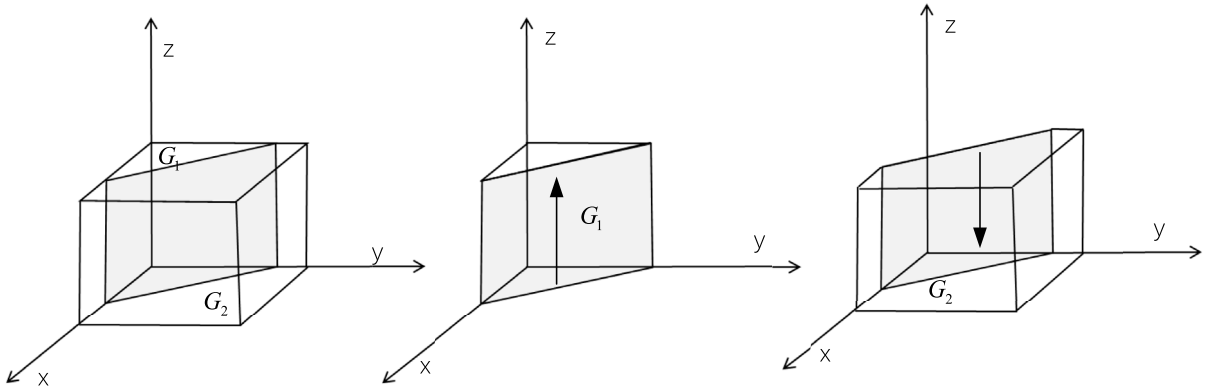

FIGURE 4
Government's strategy evolution phase diagram.

supervision strategy. The government's strategy evolution phase diagram is shown in Figure 4.

It can be seen from the phase diagram that the government's stable choice of strict stability probability is the volume of V_{G1}, and the stable probability of loose supervision is the volume of V_{G2}. The calculation method is

$$V_{G1} = \iint_D \frac{H_p + P_e + P_d - M_g - x\left(M_e + H_p + P_e\right)}{P_d + M_d} dxdy = \frac{H_p + P_e + 2P_d - 2M_g - M_e}{2(P_d + M_d)},$$

$$V_{G2} = 1 - V_{G1} = \frac{H_p + P_e - 2M_g - 2M_d - M_e}{2(P_d + M_d)}.$$

Proposition 5: The probability that the government chooses strict supervision is negatively correlated with its reward and punishment for third-party testing institutions, supervision cost, and reward for enterprises and positively correlated with the punishment of higher authorities and the punishment of enterprises and third-party testing institutions

Proof: Calculating the first-order partial derivative of each element of the probability V_{G1}, we can obtain $\frac{\partial V_{G1}}{\partial M_e} < 0, \frac{\partial V_{G1}}{\partial M_g} < 0, \frac{\partial V_{G1}}{\partial H_p} > 0, \frac{\partial V_{G1}}{\partial P_e} > 0, \frac{\partial V_{G1}}{\partial P_d} > 0, \frac{\partial V_{G1}}{\partial (M_d + P_d)} < 0.$ Therefore, the probability of strict supervision by the government is negatively correlated with its rewards and punishments for third-party testing institutions, regulatory costs, and rewards for enterprises and positively correlated with the penalties imposed by higher authorities on them and their penalties on enterprises and third-party testing institutions.

Proposition 5 shows that the greater the punishment set by the government, the more it can promote the low-carbon renovation of high-carbon emission enterprises, but its supervision will be weakened. Increased incentives for high-carbon emission enterprises and third-party testing machine are conducive to third-party testing institutions to remain neutral to protect the quality of low-carbon renovation of high-carbon emission enterprises.

Proposition 6: In the evolution process, the probability of strict government supervision decreases with the probability of third-party testing institutions refusing rent-seeking or the probability of high-carbon emission enterprises choosing low-carbon production.

Proof: When $x < \frac{H_p + P_e + P_d - M_g - y(P_d + M_d)}{M_e + H_p + P_e}$, $y < y^*$, $Q(y) > 0$, $\frac{dF(z)}{dz}|_{z=1} < 0$, $y = 1$ is the probability of the evolutionary equilibrium strategy. Conversely, $y = 0$ is an evolutionary equilibrium strategy. Therefore, as the probability of high-carbon emission enterprises choosing low-carbon production or the probability of third-party testing institutions choosing to refuse rent-seeking increases, the probability of strict government supervision decreases.

Proposition 6 shows that the probability of strict government supervision is affected by the strategic choice of third-party testing institutions and high-carbon emission enterprises. When the third-party testing institutions with higher fairness or high-carbon emissions enterprises choose low-carbon renovation, the government's strict supervision will decline, prone to regulatory deficiencies.

4.4 Strategy stability analysis of the tripartite evolutionary game

By analyzing the evolution of the strategy selection of the whole evolution system, the equilibrium point of the system can be obtained from $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$. The equilibrium point of the system is as follows:

$$E_1(0,0,0), E_2(1,0,0), E_3(0,1,0), E_4(0,0,1),$$
$$E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), E_8(1,1,1),$$
$$E_9\left(1, \frac{P_d - M_g - M_e}{P_d + M_d}, \frac{-T_p}{P_d + M_d}\right), \quad E_{10}\left(0, \frac{H_p + P_e + P_d - M_g}{P_d + M_d}, \frac{B_t - T_p}{P_d + M_d}\right),$$
$$E_{11}\left(\frac{H_p + P_e + P_d - M_g}{P_e + M_e + H_p}, 0, \frac{c_l - c_h - B_t}{P_e + M_e}\right), \quad E_{12}\left(\frac{H_p + P_e - M_g - M_d}{H_p + P_e + M_e}, 1, \frac{c_l - c_h}{P_e + M_e}\right),$$
$$E_{13}\left(\frac{B_t - T_p}{B_t}, \frac{c_h - c_l + B_t}{B_t}, 0\right), \quad E_{14}\left(\frac{B_t - T_p - P_d - M_d}{B_t}, \frac{c_h - c_l + B_t + P_e + M_e}{B_t}, 1\right).$$

Due to $0 \le x, y, z \le 1$, E_9, E_{14} are meaningless; therefore, it is discarded in the subsequent analysis. $E_{10} \sim E_{13}$ is meaningful only when satisfying some conditions. According to the tripartite replicator dynamic equation $F(x), F(y), F(z)$, the partial

TABLE 2 Possible equilibrium points and stability of the game system.

Equilibrium point	Jacobian matrix eigenvalue		Stability conclusion
	$\lambda_1, \lambda_2, \lambda_3$	Real symbol	
$E_4(0,0,1)$	$M_g - P_e - P_d - H_p, M_d + P_d + T - B_t, B_t + c_h - c_l + M_e + P_e$	$(-,\times,\times)$	Uncertain
$E_5(1,1,0)$	$c_h - c_l, -T_p, -M_e - M_d - M_g$	$(-,-,-)$	*ESS*

' − ' means the real part of the eigenvalue is negative; ' × ' means the real part of the eigenvalue is uncertain.

derivative of x, y, z should be calculated. We can obtain the Jacobian matrix of the tripartite evolutionary game system.

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix},$$

where

$$\begin{aligned}
J_1 &= (1-2x)\left[c_h - c_l + B_t - yB_t + z(M_e + P_e)\right], \\
J_2 &= (x - x^2)(-B_t), \\
J_3 &= (x - x^2)(M_e + P_e), \\
J_4 &= (y - y^2)B_t, \\
J_5 &= (1-2y)\left[T_p - B_t + xB_t + z(P_d + M_d)\right], \\
J_6 &= (1-2y)(P_d + M_d), \\
J_7 &= (z - z^2)\left(-M_e - H_p - P_e\right), \\
J_8 &= (z - z^2)(-P_d - M_d), \\
J_9 &= (1-2z)\left[H_p + P_e + P_d - M_g - x\left(M_e + H_p + P_e\right) - y(P_d + M_d)\right].
\end{aligned}$$

In the tripartite replication dynamic system, $E_{10} \sim E_{13}$ is a non-asymptotic stable state, and only the asymptotic stability of $E_1 \sim E_8$ is discussed. According to the Lyapunov method, $E_1, E_2, E_3, E_6, E_7, E_8$ is an unstable point. The possible equilibrium points and stability of the game system are shown in Table 2.

Proposition 7: When the rent-seeking cost of high-carbon emission enterprises is greater than the speculative cost of third-party testing institutions and the government's reward and punishment for it, the sum of the production cost difference and the rent-seeking cost is higher than the sum of the government's reward and penalty, the replicator dynamic system has a stable point $E_4(0,0,1)$, $E_5(1,1,0)$.

Proof: When the rent-seeking cost of high-carbon emission enterprises is greater than the speculative cost of third-party testing institutions and the government's reward and punishment, where $M_d + P_d + T_p - B_t < 0$, the sum of enterprise production cost difference and rent-seeking cost is higher than the sum of reward and punishment, where $B_t + c_h - c_l + M_e + P_e < 0$; the cost of government regulation is lower than the amount of punishment, which is consistent with the objective reality of government regulation, where $M_g - P_e - P_d - H_p < 0$. Therefore, $\lambda_1, \lambda_2, \lambda_3$ of the equilibrium point $E_4(0,0,1)$ is the negative real part, and $E_4(0,0,1)$ is the asymptotic stability point of the system.

Proposition 7 shows that when the government's rewards and punishments for third-party testing institutions and high-carbon emission enterprises are relatively small and the speculative gains when enterprises and third-party testing institutions choose rent-seeking strategies are high, according to the different initial points of the three-party strategy selection, the evolution of the strategy portfolio is stable at (high-carbon production, rent-seeking, and strict supervision) and (low-carbon production, refuse rent-seeking, and loose supervision). At this time, the regulatory effectiveness of the government has declined, and high-carbon production enterprises and third-party testing institutions easily form a cooperative relationship, resulting in poor quality of low-carbon renovation. In order to avoid the emergence of such phenomena, the government should increase the intensity of rewards and punishments and test the effectiveness of the reward and punishment mechanism.

Proposition 8: When the reward and punishment for third-party testing institutions and high-carbon emission enterprises is greater than their speculative income, the sum of the difference in production costs and rent-seeking costs of enterprises is higher than the government's reward and punishment, and the replicator dynamic system has only one equilibrium point $E_5(1,1,0)$.

Proof: When the rewards and punishments for third-party testing institutions and high-carbon emission enterprises are greater than their speculative gains, where $M_e + P_e > c_l - c_h - B_t, M_d + P_d > B_t - T_p$, $E_4(0,0,1)$ exists a positive real part, this is not an equilibrium point. At this point, the replicator dynamic system has only one equilibrium point $E_5(1,1,0)$.

Proposition 8 shows that the government's rewards and punishments for third-party testing institutions and high-carbon emission enterprises are greater than their speculative gains, so as to effectively prevent the emergence of (high-carbon production, rent-seeking, and strict supervision) strategy combinations. At this time, the government's reward and punishment for high-carbon emission enterprises should be greater than their production cost difference and rent-seeking cost, while the reward and punishment for third-party testing institutions should be greater than their speculative income. Thus, a reasonable reward and punishment mechanism can effectively promote the low-carbon renovation of high-carbon emission enterprises and can constrain the rent-seeking behavior of third-party testing institutions to protect the quality of low-carbon renovation.

5 Simulation analysis

The Chinese government has provided many positive policies for low-carbon renovation, and it has also introduced many negative policies for traditional high-carbon industries, including providing R&D subsidies for low-carbon renovation, upgrading low-carbon

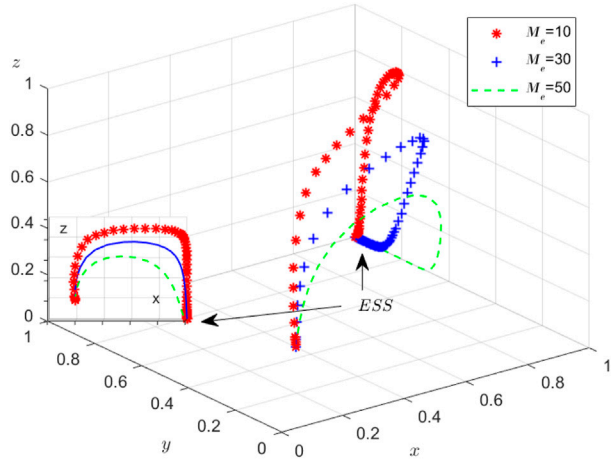

FIGURE 5
Influence of rewards of low-carbon renovation on system evolution.

supporting facilities and infrastructure, increasing carbon tax, and encouraging high-carbon emission enterprises. Low-carbon renovation gives priority to the development of low-carbon industries. For example, in January 2023, the Industrial and Information Bureau of Jinan City, Shandong Province, announced a list of enterprises that received financial incentives for industrial green development. ZTJ Group's Construction Technology Co., Ltd., is rewarded by the government department. The company's main business scope is the research and development of new technologies for building materials and the production of traditional building materials. According to the requirements of the local government, the company has implemented low-carbon renovation since 2021, developed new green technologies, and improved production processes. At the end of 2022, the low-carbon renovation of building material production was basically completed, and it obtained the government's green development incentive funds of 200,000 Yuan. Based on the aforementioned background, this paper takes the low-carbon renovation of traditional high-carbon emission industries in China as the research background and studies the quality supervision of low-carbon renovation of high-carbon emission enterprises under the government reward and punishment mechanism.

In order to verify the effectiveness of the evolutionary stability analysis, this paper refers to the research results of Yue and Lin (2019), Xu et al. (2021), and Liu et al. (2021) and combines the reality to assign the model. The case is based on the low-carbon renovation of the boiler burner of ZTJ Group Construction Technology Co., Ltd. The cost of the production line after the low-carbon renovation is about 960,000 CNY higher than that before the renovation. In order to facilitate the calculation, the production cost difference is 90. As mentioned previously, after the completion of the low-carbon renovation, the local government awards 200,000 CNY, taking into account the increase in its social benefits, the total income value of 350,000 CNY. Therefore, the parameter for high-carbon emission enterprises rewards is 35. Referring to the work of Xi'an, the government gives each annual 200,000–500,000 CNY incentive policy for no bad business behavior of the third-party inspection and testing institutions; the parameter for third-party testing institution rewards is 25. According to the assumption that the rent-seeking cost should be lower than the government's reward for enterprises and the cost of renovation and much higher than the government's reward for third-party testing institutions, the rent-seeking cost parameter is valued at 40. The fundamental purpose of the government's reward and punishment mechanism is to encourage high-carbon emission enterprises to carry out low-carbon renovation. Therefore, the punishment parameters are assigned according to the principle that the punishment is lower than the reward. This study uses MATLAB 2022a software to simulate the data. Array 1 $c_l - c_h = 90, M_e = 35, P_e = 25, M_d = 25, P_d = 15, T_p = 10, H_p = 30, B_t = 40$, which satisfies condition $M_e + P_e > c_l - c_h - B_t, M_d + P_d > B_t - T_p$ in Proposition 8, and the main results are presented in the following sections.

5.1 Influence of the reward and punishment mechanism on system evolution

5.1.1 Rewards and punishments for high-carbon emission enterprises on system evolution

In order to investigate the influence of the reward intensity of low-carbon renovation of high-carbon emission enterprises on the process and results of evolutionary game, the government's reward M_e for low-carbon renovation of enterprises is assigned, $M_e = 10, 30, 50$, and the dynamic equation is replicated 50 times over time. The results are shown in Figure 5.

Figure 5 shows that in the process of evolution to a stable point, the increase in the reward amount for low-carbon renovation of high-carbon emission enterprises can accelerate the evolution speed of their low-carbon renovation. With the increase in the reward amount, the supervision of government regulatory departments will be reduced, and the probability of third-party testing institutions refusing rent-seeking will increase. Therefore, the government should strengthen the supervision of the quality of low-carbon renovation while increasing the incentives for low-carbon renovation to promote the low-carbon renovation of high-carbon emission enterprises. In the process, the supervision role of third-

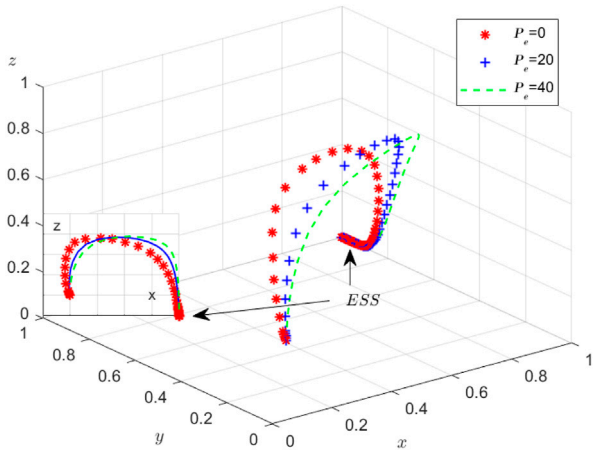

FIGURE 6
Influence of high-carbon production punishment on system evolution.

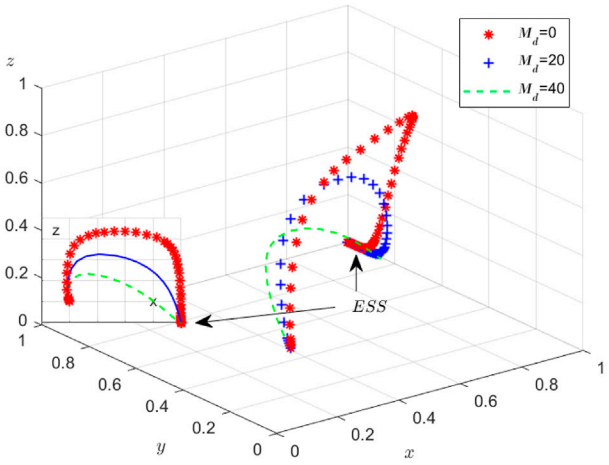

FIGURE 7
Influence of refusing rent-seeking rewards on system evolution.

party testing institutions can be appropriately played to ensure the quality of low-carbon renovation.

In order to investigate the influence of the punishment of high-carbon production of high-carbon emission enterprises on the process and results of evolutionary game, the government's punishment P_e for high-carbon production of enterprises is assigned $P_e = 0, 20, 40$, respectively, and the dynamic equation is replicated 50 times over time. The results are shown in Figure 6.

Figure 6 shows that the increase in the penalty amount of high-carbon production can promote enterprises to carry out low-carbon renovation, but the evolution speed is lower than that of the reward mechanism. With the increase in the penalty amount, based on the consideration of the penalty income, the government tends to strictly supervise. Therefore, when promoting low-carbon renovation of enterprises, the government should formulate a reasonable reward–punishment mechanism, implement the strategy of giving priority to the reward mechanism and supporting the punishment mechanism, and increase the subjective will of low-carbon renovation of enterprises.

5.1.2 Influence of reward and punishment of third-party testing institutions on system evolution

In order to investigate how the reward for third-party testing institutions affects the evolutionary game process and results, the government's reward M_d for third-party testing institutions to refuse rent-seeking is assigned, $M_d = 0, 20, 40$, and the dynamic equation is replicated 50 times over time. The results are shown in Figure 7.

Figure 7 shows that the increase in the government's reward for third-party testing institutions to refuse rent-seeking will increase the probability of refusing rent-seeking, but the probability of strict supervision will decrease. Therefore, the government should formulate a reasonable reward and punishment mechanism when

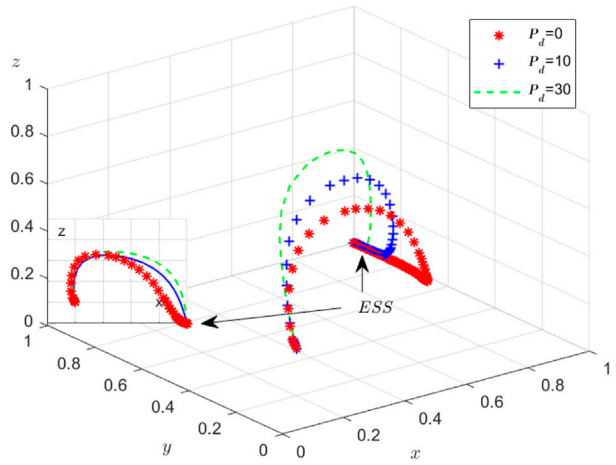

FIGURE 8
Influence of rent-seeking punishment on system evolution.

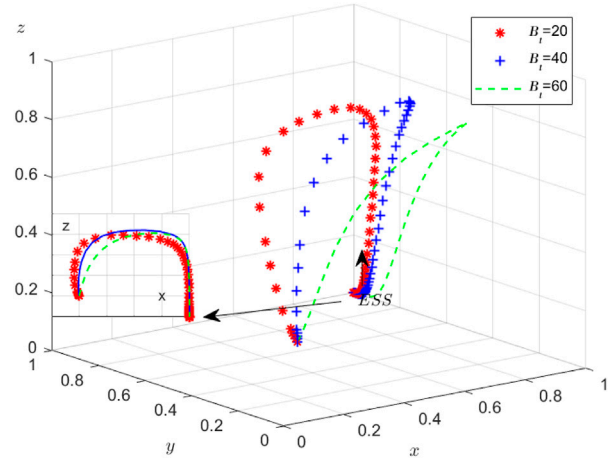

FIGURE 9
Influence of rent-seeking cost on the evolutionary system.

hiring third-party testing institutions, take rewards as part of their service fees, strengthen their assessment, and effectively protect the fairness of third-party testing institutions.

In order to investigate how the punishment for rent-seeking of third-party testing institutions affects the evolutionary game process and results, the government's punishment P_d for rent-seeking of third-party testing institutions is assigned, $P_d = 0, 10, 30$, and the dynamic equation is replicated 50 times over time. The results are shown in Figure 8.

Figure 8 shows that as the government's penalty for rent-seeking by third-party testing institutions increases, the probability of refusing rent-seeking also increases, while the probability of low-carbon renovation of high-carbon emission enterprises and the probability of strict government supervision increase. Therefore, the punishment of third-party testing institutions to protect the impartiality of third-party testing institutions is an important measure to promote the low-carbon renovation of high-carbon emission enterprises.

5.2 Influence of rent-seeking cost on system evolution

In order to investigate the influence of rent-seeking cost of high-carbon emission enterprises on the process and result of evolutionary game, the rent-seeking cost B_t of high-carbon emission enterprises is assigned, $B_t = 20, 40, 60$, and the dynamic equation is replicated 50 times over time. The results are shown in Figure 9.

Figure 9 shows that in the process of evolution, with the increase in rent-seeking costs of high-carbon emission enterprises, government supervision has not changed much, but the

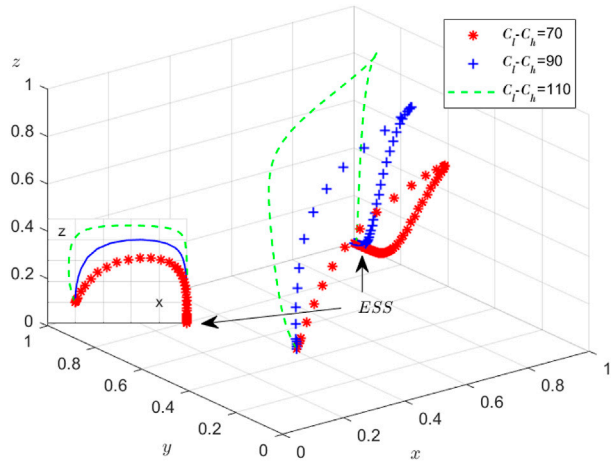

FIGURE 10
Influence of the difference between the productions costs on the evolutionary system.

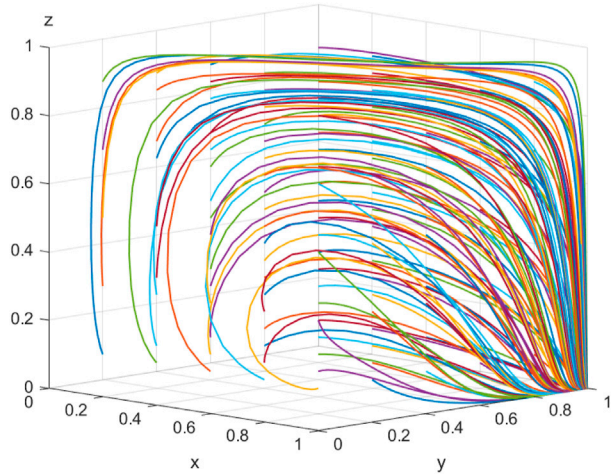

FIGURE 11
Array 1 evolution results.

probability of low-carbon renovation has increased, while the probability of third-party testing institutions refusing rent-seeking has decreased. Therefore, the government can increase the cost of rent-seeking and reduce the probability of rent-seeking by increasing rewards and punishments for third-party testing institutions and enterprises, reducing production qualification and managing negative lists.

5.3 Influence of enterprise production cost difference on the evolutionary system

In order to investigate the influence of the difference between the production cost after the low-carbon renovation of high-carbon emission enterprises and the high-carbon production cost on the evolutionary game process and results, the difference $c_l - c_h$ in the production cost is assigned $c_l - c_h = 70, 90, 110$, and the dynamic equation is replicated and evolved 50 times over time. The results are shown in Figure 10.

Figure 10 shows that in the process of evolution, with the increase in the production cost difference, the probability of strict government supervision increases, while the probability of enterprises choosing low-carbon renovation decreases. Therefore, under the premise of certain sales revenue, the difference in the production cost is the key factor for high-carbon emission enterprises to carry out low-carbon renovation, which is also one of the restrictive factors for the low-carbon renovation of most high-carbon emission enterprises. The system evolution results show that the government can reduce the production cost difference by adopting subsidies and tax incentives and improving industrial supporting services. Enterprises can improve production efficiency and reduce production cost difference through

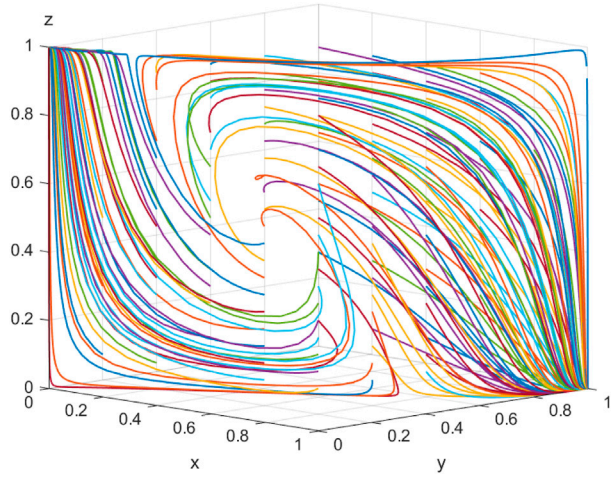

FIGURE 12
Array 2 evolution results.

technological innovation and supply chain optimization, forming a benign closed loop of mutual support between enterprises and the government.

5.4 Stability analysis of the evolutionary strategy

Array 1 satisfies the conditions in Proposition 8. To verify the stability of the evolutionary strategy, array 2 $c_l - c_h = 90, M_e = 25, P_e = 15, M_d = 15, P_d = 10, T_p = 10, H_p = 30, B_t = 40$ is used to satisfy the conditions in Proposition 7. The two sets of values are evolved 50 times over time from different initial combination strategies. The results are shown in Figures 11, 12.

As shown in Figure 11, under the condition of satisfying Proposition 8, array 1 has only one evolutionary stable strategy $E_5(1,1,0)$, which is consistent with the inference result. As shown in Figure 12, there are two evolutionary stable points $E_4(0,0,1)$ and $E_5(1,1,0)$ in the system under the condition of Proposition 7, which is consistent with the inference result of inference 7. Thus, the simulation results are consistent with the inference and effective. Therefore, the government's reward and punishment mechanism for high-carbon emission enterprises should be higher than the sum of production cost difference and rent-seeking cost; the reward and punishment mechanism for third-party testing institutions should be greater than their speculative gains.

6 Conclusion

6.1 Research conclusion and suggestions

Under the government reward and punishment mechanism, the possible rent-seeking behavior between high-carbon emission enterprises and third-party testing institutions in the process of low-carbon renovation quality acceptance is considered. A tripartite evolutionary game model was constructed between the government, high-carbon emission enterprises, and third-party testing institutions to analyze the stability of the strategy selection of all parties and the stability of the equilibrium strategy combination of the game system. This paper explores the influence of the government's reward and punishment mechanism, rent-seeking cost, and production cost difference on the evolution of the game system and verifies the validity of the analysis conclusion by MATLAB 2022a numerical simulation. The conclusions of this paper are as follows:

1) The increase in the reward and punishment mechanism on the government side will promote the low-carbon renovation of high-carbon emission enterprises and the strategic choice of third-party testing institutions to refuse rent-seeking, but the increase in the reward will reduce the probability of strict government supervision, which is not conducive to the government's performance of regulatory duties and is prone to inadequate supervision.
2) A reasonable reward and punishment mechanism can effectively promote the low-carbon renovation of high-carbon emission enterprises and regulate the behavior of third-party testing institutions, but the government in the development of the reward and punishment mechanism must be combined with the actual situation of the parties. The sum of the reward and punishment mechanism for high-carbon emission enterprises should be higher than the sum of production cost difference and rent-seeking cost. The sum of the reward and punishment mechanism for third-party testing institutions should be greater than their speculative income, so as to ensure the quality of low-carbon renovation of high-carbon emission enterprises.
3) The higher the cost of rent-seeking, the higher the probability of third-party testing institutions choosing rent-seeking behavior, which is not conducive to government regulation of the quality of low-carbon renovation. The government can curb rent-seeking behavior by increasing the amount of penalties, degrading

production qualifications, and managing negative lists, which is also an effective way to avoid substandard low-carbon renovation quality.

4) Under the premise of certain sales revenue, the cost difference between low-carbon production and high-carbon production is the key factor for enterprises to decide whether to carry out low-carbon renovation. The greater the production cost difference, the lower the willingness of enterprises to carry out low-carbon renovation. The government can reduce the difference in production costs by means of subsidies and tax incentives and improve industrial supporting services; enterprises can improve production efficiency, reduce production cost difference, and achieve a win–win situation between the government and enterprises through technological innovation and optimization of supply chain.

Based on the research results, under the realistic background that the government encourages the low-carbon renovation of traditional high-carbon emission enterprises, this study proposes the following suggestions:

1) The government should establish and improve the types of subsidies and punishments, not blindly set rewards and punishments, and promote the low-carbon renovation of high-carbon emission enterprises in various ways to enhance the willingness of enterprises to actively transform. For example, in the early stage of low-carbon renovation of enterprises, the willingness of enterprises to transform is low. At this time, incentives can be appropriately increased to mobilize the enthusiasm of enterprises for low-carbon renovation. In the late stage of low-carbon renovation, after the low-carbon development of the industry has become a trend, it can reduce incentives and increase penalties to guide enterprises to complete low-carbon renovation.
2) In order to avoid the phenomenon of rent-seeking between enterprises and third-party testing institutions, the punishment for third-party testing institutions should be greater than their speculative income, so as to fundamentally curb the generation of rent-seeking behavior. For example, the establishment of a third-party testing agency management approach, the rent-seeking behavior as a major breach of trust, once found to cancel its testing qualification, included in the industry blacklist, in order to protect the quality of low-carbon renovation of high-carbon emission enterprises.
3) In order to ensure the high-quality completion of low-carbon renovation of high-carbon emission enterprises, in addition to avoiding rent-seeking behavior between them and third-party testing institutions, the difference between low-carbon production costs and high-carbon production costs should also be reduced. For example, in the early stage of low-carbon renovation, the government gives appropriate subsidies according to the production volume, improves the infrastructure of supporting services, encourages independent innovation of enterprises, improves production efficiency through technical means, reduces the difference in production costs, and promotes traditional high-carbon emission enterprises to complete low-carbon renovation with high quality through multiple channels.

6.2 Research limitations

This paper only considers the quality supervision of low-carbon renovation of high-carbon emission enterprises under asymmetric information and bounded rationality, and it fails to consider the impact of market demand, sales income difference, and technical level on low-carbon renovation of high-carbon emission enterprises. In order to facilitate the analysis, the rent-seeking cost of the enterprise is equivalent to the rent-seeking income of the third-party testing institutions, and it is not split according to the different stakeholders. In addition, the influence of game order is not considered. Therefore, it will be the next research direction to introduce the influencing factors such as market mechanism and enterprise resource level, analyze the rent-seeking cost in depth, and study the mechanism of each factor on the low-carbon renovation of high-carbon emission enterprises.

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

XW constructed the evolutionary game model and performed simulation analyses. CY designed the research framework and methodology. QH was responsible for the literature analysis. YX edited the manuscript. All authors contributed to the manuscript and approved the submitted version.

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Conflict of interest

Authors XW and YX were employed by China Railway Construction Investment Group Co., Ltd.

The remaining 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.

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Agricultural socialized services to stimulate the green production behavior of smallholder farmers: the case of fertilization of rice production in south China

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Introduction: This study investigates the impact of Agricultural Socialized Services (ASSs) on the green production behavior (GPB) of smallholder farmers in the main rice production region of southern China. The research aims to address the gap in understanding the relationship between ASSs and the adoption of sustainable agricultural practices by smallholder farmers.

Methodology: Data was collected from 741 smallholder farmers in Hunan, Jiangxi, and Zhejiang provinces using a structured questionnaire. A probit model was employed to examine the relationship between ASSs and smallholder farmers' GPB.

Results and Discussion: The study revealed that ASSs have a significant and positive impact on smallholder farmers' GPB. Farmers who received ASSs tended to adopt more sustainable agricultural practices such as using organic fertilizer and soil-tested formula fertilizer. The findings of this study have important implications for policymakers. The results suggest that policymakers should prioritize the development of services to agricultural producers and strengthen Agricultural Service Systems. This can be achieved through optimizing the public administration service system, establishing joint service organizations, and creating a good financial and legal service environment. By doing so, policymakers can promote the adoption of sustainable agricultural practices and the overall development of the agricultural sector.

KEYWORDS

agricultural socialized services, green production behaviour, smallholder farmers, rice production, China

1 Introduction

Smallholder farmers, commonly, farmers with less than 2 ha of cultivated land, produce about 80% of the world's food (Maass, 2013; FAO, 2014), which is vital to the global sustainable development (Fan and Rue, 2020). Smallholder farmers have long been at the centre of agricultural and rural development policies and strategies in the developing world (Bagheramiri and KeshvarzShaal, 2020). Despite their vital role, however, they are often

more vulnerable to poverty and food insecurity (Alpízar et al., 2020; Adetoso et al., 2022). Consequently, agricultural practices conducted by smallholder farmers can be characterized as unproductive, unprofitable, environmentally-unfriendly and, as a result, unsustainable (Kandpal, 2021). Currently, in response to these critical challenges, the government of China identified two strategies: First, facilitating agricultural land transfer and scaling-up agricultural management system, thereby establishing large-scale agricultural operations, widely explained as agricultural economy of scale (Cao et al., 2020). Secondly, improving the quality of agricultural production operated by smallholder farmers through providing adequate services (Zhang, 2019; Yu et al., 2020). It's believed that providing multidimensional services to smallholders by creating special business enterprises can address these significant barriers and mobilize them towards sustainable agricultural development. Therefore, it's critical to investigate the effects of these services in changing the mode of smallholders' agriculture.

Agriculture is a major contributor to carbon emissions, and reducing these emissions is essential for mitigating the effects of climate change (Thomson et al., 2014; Karimi et al., 2018; Wagena and Easton, 2018; Sarkar et al., 2020; FAO, 2014; Lynch et al., 2021). For example, a study by FAO (2017) found that agriculture accounted for over one-quarter of energy-related CO_2 emissions in China. These findings highlight the urgent need for sustainable agricultural practices that can reduce carbon emissions and promote environmental sustainability. In this context, studying green production behavior of smallholder farmers in China becomes even more critical, as it could potentially identify approaches to mitigate the impact of agricultural activities on the environment (Li et al., 2020). By adopting sustainable agricultural practices, such as the use of organic fertilizers and conservation tillage, farmers can reduce their carbon footprint and contribute to the global effort to combat climate change (Huang et al., 2018). Therefore, investigating the impact of Agricultural Socialized Services (ASSs) on green production behavior is crucial, as these services provide smallholder farmers with access to information, resources, and technologies necessary for adopting sustainable agricultural practices and reducing carbon emissions.

The Chinese government promotes a special organized service system called agricultural socialized services (henceforth ASSs) to provide multidimensional services to smallholder farmers. ASSs refer to the various agricultural services provided by the social economic organizations to meet the needs of agricultural production and the business entities of agricultural production (Han et al., 2021; Salam et al., 2021; Yi et al., 2021). In recent years, ASSs have garnered the attention of smallholder farmers. Typical ASSs include agricultural machinery services, soil test-based, and organic fertilizer services, crop protection services, and other services put in place to support the sustainability of smallholders' agriculture. At present, ASSs serve as a key tool to improve the quality and productivity of agricultural production for smallholder farmers (Huan et al., 2022).

The expense of smallholders for the purchase of ASSs increased from 89.9 yuan per mu in 2004 to 272.26 yuan in 2019, accounting for 50% of the agricultural production costs (Mao et al., 2021). As of the end of 2020, the number of ASSs organizations in China had exceeded 900,000, and the agricultural production trusteeship service had exceeded 1.6 billion mu, including over 900 million mu of food crops, and over 70 million smallholder households. The government has also continually introduced a range of policies and measures to support the development of ASSs organizations. The report of the 19th National Congress of the Communist Party of China (herein after CPC) proposed to improve the ASSs system and realizing the organic connection between smallholder farmers and modern agriculture development. In 2021, the No.1 Document of the CPC again proposed the development and expansion professional ASSs organizations and the introduction of advanced and applicable varieties, inputs, technologies, and equipment to smallholder farmers. It can be seen that China's agricultural management departments have taken the ASSs as an important starting point to change the agricultural development mode. Moreover, ASSs are considered an effective path to guide smallholder farmers in achieving the organic connection of green production and modern agriculture. Therefore, in-depth efforts to investigate the impact of the ASSs on smallholders farmers agricultural production is an important response to practical problems.

In China, southern regions account for a majority of rice production, with approximately 90% of the country's rice grown in this area. However, despite this dominance in rice cultivation, small-scale farmers in these regions face significant challenges due to the impact of arable land area and population size. These farmers have very limited land area available for farming, which makes it difficult to achieve sustainable agricultural practices. Additionally, small-scale farmers in southern China have weak green production awareness and technical support, which exacerbates their difficulties in producing crops. The lack of knowledge and resources among small-scale farmers can lead to inefficient use of fertilizer, resulting in environmental pollution, decreased crop yields, and ultimately, economic losses (Guo et al., 2021). Therefore, it is crucial to provide agricultural socialized services to support these farmers and promote sustainable, efficient, and environmentally-friendly agricultural practices. By doing so, we can enhance green production behavior in smallholder farmers, particularly in the fertilization of rice production in southern China, and promote more sustainable and efficient use of resources.

Farmers' green agricultural production behaviour (henceforth GPB) refers to the intention of farmers to apply eco-friendly agricultural practices to improve the quality and safety of agricultural products thereby mediating agricultural environmental pollution (Gong et al., 2019; Shen et al., 2020; Xiao et al., 2022; Zhang et al., 2022). GPB usually has five main objectives: 1) pollution reduction 2) energy conservation 3) consumption reduction, and 4) high-quality and high-efficiency agricultural system 5) ecological and safe agricultural production methods by creating standardized agricultural operation methods (Liu et al., 2020; Pergola et al., 2020; Khanh Chi, 2022). Farmers' GPB includes the intention of applying soil and water conservation practice, application of organic fertilizers, straw applications and other eco-friendly agricultural practices (Muktamar et al., 2016; Alemayehu et al., 2020). GPB of smallholders is affected by multidimensional factors and understanding the complex mechanism how these factors influence on agro-environmental nexus is important form a policy perspective.

The aim of this paper is to investigate the impact of Agricultural Socialized Services (ASSs) on the Green Production Behavior (GPB)

of smallholder rice farmers in south China, particularly in the application of organic and soil-tested fertilizers. The study collected survey data from three major rice production provinces in south China in 2020 and utilized an empirical model to conduct an exploratory analysis. By focusing on the most difficult agricultural management subject in China, the study provides a policy basis to encourage smallholder rice farmers to actively participate in green agricultural production and promote the high-quality development of agriculture. The study's contribution lies in measuring the level of local ASSs and avoiding endogenous problems between the production behavior of smallholder farmers and ASSs variables. Additionally, by taking the actual fertilization behavior of smallholder farmers as the main focus, the study avoids including GPBs that belong to the category of socialized services, making it easier to analyze the relationship between ASSs and the GPB of smallholder farmers. However, more elaboration is needed to clarify how ASSs can stimulate the GPB of smallholder farmers and why this is important for the development of green agricultural production.

2 Literature review

Over the past few years, literature has become increasingly interested in the multi-dimensional aspects of ASS. ASS are becoming a key tool in providing high-quality, profitable agricultural inputs to smallholder farmers (Lin et al., 2022). ASS provides a solution for farmers' employment decisions and address agricultural labor shortage (Chen et al., 2022; Cheng et al., 2022). ASS, by encouraging farmers to involve in farmland transaction market (farmland transfer-in and out), encourages smallholder farmers to participate in farmland scale management operations (Cai et al., 2022). ASS enhances crop yield and generate economic benefit (Zhang et al., 2018).

Existing studies have carried out extensive research on farmers' GPB. GPB affected by multidimensional factors. For instance, support policies for field guidance, machinery service and financial support service encourage farmers to use manure in their farmland (Zhang et al., 2022). Farmers who are members of agricultural cooperatives, obtained subsidies, and own vast agricultural lands tend to apply agricultural green production practices (Wang et al., 2018). However, unstable land tenure, small and fragmented agricultural land restrict GPB of farmers (Xu et al., 2014; Lu et al., 2019). Farmers with knowledge of agricultural land protection policies tend to apply agricultural green production practices (Cao et al., 2020). The provision of expertise and experience on the use of organic fertilisers and subsidies encourages farmers to use organic fertilisers (Vu et al., 2020; Zhang et al., 2021). These studies focused primarily on the mechanisms of factors that affect farmers' GPB. In China, the positive factors of GPB such as guidance, financial support and information provision have recently offered by ASSs.

Only few studies address the question of whether ASSs have contributes to the improvement of GPB of smallholder farmers such as the application of organic fertilizer and soil tested fertilizer by smallholders. For instance, existing studies highlighted the role of ASSs, particularly, ASS of organic and soil-tested fertilizer in improving soil quality and fertility (Han et al., 2021; Yi et al., 2021). Rice farmers who use ASSs are technically more efficient than those who do not, suggesting that organic fertilizers enable farmers to improve the agricultural green production efficiency of rice cultivation (Salam et al., 2021). ASSs encourage smallholder farmers to participate in the agricultural green revolution paradigm (Epule et al., 2015). The use of ASSs have reduced disruptions to ecosystems by inhibiting GHG emissions (Tang et al., 2019). ASSs promote agricultural cleaner production and quality development in the agricultural sector (Zhang, 2019; Ji and Li, 2020; Sun et al., 2020). Agricultural cleaner production aims to reduce the environmental impact of farming while maintaining or increasing productivity. Moreover, ASSs encourage smallholder farmers to adopt soil and water conservation practices such as crop rotation and manure application (Gideon, 2022). Recently, Huan et al. (2022) revealed that ASSs encourage farmers to adopt sustainable agricultural practices. Though ASSs emerging as an essential strategies to improve the quality and safety of smallholders' agricultural practices, the knowledge on the linkage between ASSs and GPB of smallholders is still insufficient.

3 Methods

3.1 Theoretical foundation

Macho-Stadler and Pérez-Castrillo, 2012 constructed a principal-agent model to examine the behavior of law enforcement officers. This model has attracted the attention and application of wider scholars to investigate problems such as moral hazard. Assuming that farmers are always engaged in agricultural production activities and belong to the type of risk neutrality. Farmers determine their production behavior according to the long-term effect obtained. There is two behaviors of farmers in the process of agricultural production; the behavior of implementing green agricultural practices and the behavior of non-implementing green production practices. Farmers who do not implement green production practices are mainly referred to farmers' illegal use of chemical fertilizers, pesticides, and other environmentally harmful chemicals, which is considered a moral hazard behavior.

In terms of the major factors affecting farmers' demand for chemical fertilizer, we agree that increasing production and risk avoidance are key drivers. We would like to further elaborate on the relevant theories in this regard. Behavioral economics theory suggests that farmers' decision-making can be influenced by psychological factors such as cognitive biases, emotions, and social norms. On the other hand, risk aversion theory suggests that farmers will be more cautious and conservative in their fertilizer use if they perceive high levels of risk associated with crop failure or financial loss. It is important to note that socialized services can provide support and incentives for small farmers to translate their willingness to adopt green practices into actual behavior. Socialized services can offer training programs, technical assistance, financial incentives, and access to markets, all of which can help to reduce the perceived risks of transitioning to more sustainable and environmentally friendly farming practices. In summary, behavioral economics and risk aversion theories explain the major factors affecting farmers' demand for fertilizers. Socialized services play a critical role in incentivizing the adoption of green

practices among small farmers. We will make sure to strengthen the theoretical underpinnings of our paper accordingly.

Suppose that when farmers choose to implement GPBs, they expect their agricultural production income in each period $I_1(I_1 > 0)$, C_1 represents the cost of agricultural production, represents the reward for implementing green production and ε (0 < ε < 1) represents the discount factor, then the utility function of the farmer in each period is U = I_1 + R − C_1.The expected utility flow of farmers is calculated as follows:

$$\begin{array}{c} U_1\ U_2\ \ldots\ldots\ U_t \\ I_1 + R - C_1\ I_1 + R - C_1\ I_1 + R - C_1 \end{array}$$

When farmers implement GPBs, the expected total effect is:

$$TU_1 = U_1 + \varepsilon U_2 + \cdots + \varepsilon^{t-1}U_t = (I_1 + R - C_1)\left(1 + \varepsilon + \cdots + \varepsilon^{t-1}\right) = \frac{1-\varepsilon^t}{1-\varepsilon}(I_1 + R - C_1) \quad (1)$$

Since farmers clearly know that the government and consumers cannot monitor their production behavior all the time, they do not implement safe production behavior. The government cannot easily find farmers who implement non-green agricultural production practices. Therefore, farmers have the motivation to carry out moral hazard.

In order to achieve the goal of increasing production and income, farmers may increase the application of chemical fertilizers and pesticides, and even use illegal pesticides. It is assumed that the additional income obtained by farmers without implementing GPBs is B, the production cost is C2. Assuming that the cost of farmers implementing GPBs is greater than that of farmers not implementing GPBs, that is, C2 < C1, and they still choose not to implement GPBs in subsequent periods until they are found. If farmers do not implement GPBs and are not found, their income is $B + I_1 + R - C_2$;If a farmer is found not to implement GPBs, his income is $I_2 - F - C_2$, where I_2 represents the income of farmers who are found not to implement GPBs($0 \le I_2 \le I_1$),F represents the loss or cost of farmers' failure to implement GPBs under the background of organization, market and government supervision.

Assuming that the probability of non-GPBs farmers being discovered by consumers, p is represent the government or other clients, the expected utility of farmers in each period is:

$$\begin{array}{l} U = (1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) \\ U_1 = (1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) \\ U_2 = (1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) \\ \cdots\cdots \\ (1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) \\ U_t = (1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) \end{array}$$

If farmers always choose not to implement GPBs, the expected total effect is:

$$TU_2 = U_1 + \varepsilon U_2 + \cdots + \varepsilon^{t-1}U_t \quad (2)$$
$$= \left[(1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2)\right]\left(1 + \varepsilon + \cdots + \varepsilon^{t-1}\right)$$
$$= \frac{1-\varepsilon^t}{1-\varepsilon}\left[(1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2)\right]$$
$$= \frac{1-\varepsilon^t}{1-\varepsilon}\left[(1-p)(B + I_1 + R - C_2) + p(I_2 - F - C_2) - p(I_2 - F - C_2)\right]$$

Whether farmers implement GPBs mainly depends on the extent to which these two behaviours happen which in turn affect farmers expected total utility. If the expected total utility of farmers increases after not GPBs, farmers will choose not to implement GPBs. The difference between the expected total utility of farmers implementing green production behavior (Eq. 1) and not implementing GPB (Eq. 2) is:

$$\Delta TU = TU_1 - TU_2 \quad (3)$$

in Eq. 3, Δ TU represents the increase of total utility when farmers implement GPBs. When the increase of total utility is greater than zero, farmers are willing to implement GPBs, and the more the increase of total utility, the stronger the willingness of farmers to implement GPBs.

Farmers are limited rational brokers, and their ultimate purpose in agricultural production activities is to obtain the maximum benefits. According to Eq. 3, it can be seen that whether farmers choose to implement GPBs may be affected by these factors including: rewards received by farmers from the government, cooperatives or enterprises when they implement green production behavior (R); the cost of agricultural production induced by farmers GPBs (C_1); income obtained from agricultural production when farmers implement GPBs (I_1); losses caused by the government, cooperatives, enterprises and other clients when farmers do not implement green production (F); the probability of being discovered and punished by the client when farmers do not implement GPBs (p); the extra income that farmers can get from agricultural production when they do not GPBs (B); the agricultural production income after the client finds when farmers do not implement GPBs (I_2) and agricultural production cost when farmers do not GPBs (C_2); income discount factor ε.

When we calculate the partial derivative of the above influencing factors according to Eq. 3, the impact of each factor on farmers' not to implement GPBs is as follows:

$$\frac{d\Delta TU}{dp} = \frac{1-\varepsilon^t}{1-\varepsilon}(B + R + F + I_1 - I_2) > 0 \quad (4)$$
$$\frac{d\Delta TU}{dI_2} = -\frac{1-\varepsilon^t}{1-\varepsilon}\ \mathrm{p} < 0 \quad (5)$$
$$\frac{d\Delta TU}{dF} = \frac{1-\varepsilon^t}{1-\varepsilon}\ \mathrm{p} > 0 \quad (6)$$
$$\frac{d\Delta TU}{dI_1} = \frac{1-\varepsilon^t}{1-\varepsilon}\ \mathrm{p} > 0 \quad (7)$$
$$\frac{d\Delta TU}{dR} = \frac{1-\varepsilon^t}{1-\varepsilon}\ \mathrm{p} > 0 \quad (8)$$
$$\frac{d\Delta TU}{dB} = -\frac{1-\varepsilon^t}{1-\varepsilon}(1-\mathrm{p}) < 0 \quad (9)$$
$$\frac{d\Delta TU}{dC_1} = -\frac{1-\varepsilon^t}{1-\varepsilon} < 0 \quad (10)$$
$$\frac{d\Delta TU}{dC_2} = -\frac{1-\varepsilon^t}{1-\varepsilon}\ \mathrm{P} > 0 \quad (11)$$

From the above analysis, it can be seen that if farmers do not implement the GPB, the penalty will be higher. On the other hand,

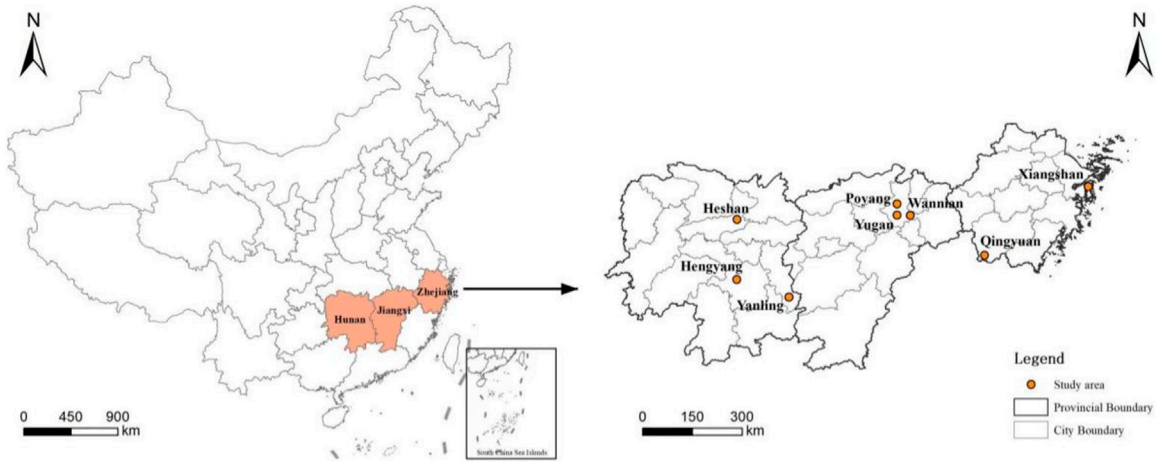

FIGURE 1
Map of the surveyed area.

the higher the income for implementing the GPB, the more rewards they will receive, and the lower the cost of implementing the GBP. This will motivate farmers to choose to implement the GPB. On the contrary, the higher the income of farmers who do not implement GPB, the higher the additional income of farmers who do not implement GPB, and the lower the cost of farmers who do not implement GPB, the greater the motivation of farmers to choose not to implement GPB.

By taking the fertilizer application behavior, this paper examines the GPB of smallholder farmers and defines the fertilization behavior with the green attribute as the application of soil testing formula fertilizer and organic fertilizer. The user behavior of soil testing formula fertilizer and organic fertilizer belong to two discrete selection variables; soil testing formula fertilizer (or organic fertilizer) has been applied, and the other soil testing formula fertilizer (or organic fertilizer) has not been applied. Smallholder farmers will be affected by many factors when using soil testing formula fertilizer and organic fertilizer. Therefore, the two decisions of smallholder farmers depend on each other. The interaction between the two decisions produces four results: Neither soil testing formula fertilizer nor organic fertilizer are applied; only soil testing formula fertilizer is applied; only organic fertilizer is applied and both soil testing formula fertilizer and organic fertilizer are applied.

3.2 Probit model

This paper establishes a bivariate probit model to analyse the impact of various factors on the green production behavior of small farmers. The model includes two binary models explained variable, the specific form of the model is as follows:

$$Y^{*}_{1i} = \beta'_{1} X_i + \varepsilon_{1i}$$
$$Y^{*}_{2i} = \beta'_{2} X_i + \varepsilon_{2i}$$

where Y^{*}_{1i} and Y^{*}_{2i} represent the selection of smallholder farmers for the application behavior of soil testing formula fertilizer and organic fertilizer respectively, i = 1, N represents the ith observation sample; X_i represents various factors affecting the behavior of small farmers in soil testing formula fertilizer and organic fertilizer application, β'_j (j = 1, 2) is the corresponding estimation coefficient. In this paper, Y_1 and Y_2 are used to represent the decision of smallholder farmers to apply soil testing formula fertilizer and organic fertilizer respectively. It is assumed that $Y_1 = 1$ means that small farmers apply soil testing formula fertilizer, and $Y_1 = 0$ means that smallholder farmers do not apply soil testing formula fertilizer. Similarly, $y_2 = 1$ means that smallholder farmers apply organic fertilizer, while $y_2 = 0$ means that small farmers do not apply organic fertilizer. Then the four results can be expressed as: (0, 0), (1, 0), (0, 1), (1, 1). Because the bivariate probit model allows the correlation between the error terms of different equations.

For the latent variable y*m, assume:

$$Yj = \begin{cases} 1 & \text{if Ym} > 0 \\ 0 & others \end{cases}$$

If smallholder farmers apply soil testing formula fertilizer, the choice of organic fertilizer is independent, then the above two equations are univariate probit model, ε_{mi} (m = 1,2) which is independent and identically distributed. However, if smallholder farmers apply soil testing formula fertilizer and organic fertilizer at the same time, the decisions are not mutually exclusive that ε_{mi} will obey multivariate normal distribution MVN (0,ψ), and the covariance matrix ψ as follows:

$$\Phi = \begin{bmatrix} 1 & \rho_{12} \\ \rho_{21} & 1 \end{bmatrix}$$

If the element value on the non-diagonal line is not 0, it indicates that the behavior of smallholder farmers applying soil-testing formula fertilizer and organic fertilizer is correlated, and the bivariate probit model should be used for regression analysis.

TABLE 1 Variable definitions and statistical description.

Variable	Definition	Mean	S.D.
Dependent variable	Yes = 1; No = 0	0.212	0.409
GPB			
Use of soil tested formula fertilizer	Yes = 1; No = 0	0.259	0.259
Use of organic fertilizer			
Independent variable			
ASSs	The actual expenditure of ASS for producing one season of rice per mu in the village where the smallholder farmers are located (yuan)	266.904	61.317
Development level of local ASS.			
Control variable			
Individual characteristics	Actual age of respondents (age)	61.690	9.558
Age	Education years of respondents (years)	3.984	3.118
Education	Years of migrant work of respondents (years)	4.574	6.599
Migrant work experience			
Family characteristics	No. of training (times)	0.433	1.326
Technical training	Total household income in 2019 (10,000 yuan)	9.523	1.058
Income level	Agricultural income/total household income in 2019 (%)	0.291	0.338
Proportion of agricultural production income	No. of college students in family members (person)	0.290	0.584
Human capital			
Farmland characteristics	Actual cultivated land area (mu)	4.652	3.358
Farmland area	Number of plots/actual cultivated plots (block/mu)	1.288	1.888
Farmland fragmentation	Flat = 1; A little slope = 2; Large slope = 3	1.827	0.788
Farmland levelling	1 = very poor; 2 = poor; 3 = general; 4 = better; 5 = very good	3.290	0.864
Farmland fertility			
Village characteristics	Distance to the nearest town (km)	5.713	4.062
Geographical position	Yes = 1, No = 0	0.173	0.378
Policy publicity			

The cost of farmers' agricultural production is related to the market and farmers' ability. Whereas, the income of farmers' agricultural products is related to the market. The probability of farmers not implementing green production behavior being found, as well as punishment and rewards obtained from implementing green production behaviors are related to the organization, the market, and the government. The analysis of the formation mechanism of green production behavior shows that whether smallholder farmers adopt green production technology is mainly affected by four factors: farmers themselves, the market, the organization, and the government (Liu et al., 2020). ASSs can enhance farmers' awareness and ability of small farmers of green agricultural production. ASSs support smallholder farmers to obtain better market information symmetry. Moreover, ASSs reduce the cost of smallholder farmers adopting green production technology and then promote smallholder farmers to adopt GPBs. Based on the above analysis, the study puts forward the hypothesis:

H1. ASSs have a positive impact on GPB of smallholder farmers in general.

H2. Smallholder farmers who obtained ASSs tend to apply organic fertilizer and soil-tested formulas more than those who do not.

Farmers' production behavior has both positive and negative external effects. In fact that farmers also judge the impact of their production behavior as it drives extensive attention from the government, social organizations, and consumers. If farmers do not implement green production, they may not be rewarded by agricultural cooperation organizations. The market or the government investigates and identifies farmers who do not implement green production. As a result, the reputation of the village will decline and affect the sales of agricultural products. Farmers who do not implement green production may be also excluded from other farmers who implement green production. On the contrary, if farmers choose to implement green production, they do not need to bear the huge

TABLE 2 Estimation results of the covariance matrix of the bivariate probit equation.

	Soil-tested formula fertilizer	Organic fertilizer
Soil-tested formula fertilizer	1	0.138***
Organic fertilizer	0.138***	1

Note: *, **, *** indicate statistical significance at the level of 10%, 5% and 1%, respectively.

psychological pressure and do not worry about being sampled by the organization, market, or government. They will earn a reputation for themselves and promote the sales of agricultural products due to long-term moral behaviors. Accordingly, this study consider internal and external factors, and theoretically analyses the main influencing factors of farmers' GPBs.

4 Data collection

The data utilized in this study were collected from rice planting smallholder household survey carried out between July and August 2020. A combination of stratification (counties and districts) and random sampling approach (village and towns) was used to collect the relevant data. Map of the study area is indicated in Figure 1. First, we purposively selected Hunan, Jiangxi and Zhejiang province, because they are the largest rice producing hub in the south China and are responsible for more than 25 percent of national rice production. Moreover, these provinces have a conducive climatic condition for rice production.

A total of 800 questionnaires were distributed, and 741 valid samples met the requirements of this study, with an effective rate of 92.63%. The questionnaire was formulated in accordance with the steps of design, pre-investigation, and finally editing the questionnaire to ensure that the content was clear, properly understood, and accepted by farmers in the face-to-face interviews. The interviews with farmers were conducted by a group of 12 research experts who are the members in our research team. Before the survey, to prove the trustworthiness and reliability of the survey data, the experts undertook training to ensure that the members fully understood the relevant issues in the questionnaire. The survey targeted rice farmers who use soil tested and organic fertilizer. The raw data were handled and analysed using stata14 to facilitate analysis.

Second, eight counties with higher rice production intensity were selected. Hengyang County, Yanling County and Yiyang County were sampled in Hunan; Wannian County, Poyang County and Yugan county were selected from Jiangxi province and Qingyuan County and Xiangshan County were selected from Zhejiang province. Third, households were selected from each counties based on the accessibility of ASSs including 228 households from counties in Hunan province; 334 households in Jiangxi province and 125 households in Zhejiang province. A total of 741 representative households were selected. Finally, a total of 800 questionnaires were distributed and 725 valid samples met the requirement of this study, with an effective rate of 90.63 percent.

In the selection of sample farmers, the regional development level, geographical location and relevant agricultural natural resource endowment were fully considered. The questionnaire was prepared in English and later translated into Chinese. We then trained the enumerators and conducted a pre-test to re-check the validity of the interview process. Face-to-face interviews were monitored by the authors and carried out by enumerators who are members of the research group and able to speak both Mandarin and the local language. In terms of survey content, the questionnaire covers the rice production season of smallholder farmers' from 2018 to 2019, and data such as basic characteristics of smallholder farmers' family endowment, purchase of ASSs, cultivated land management, geographical location of villages and other relevant data according to the purpose of this study were collected.

4.1 Variable selection and descriptive statistics

The dependent variable in this study is the GPB, which is the behavior of smallholder farmers applying soil-tested formula fertilizer and organic fertilizer. Therefore, there are two dependent variables in this paper; the use of soil-tested formula fertilizer and the use of organic fertilizer. If farmers applied any of these GPB, they will assign the value 1, otherwise the value will be 0. In this study, smallholder farmers' GPB considered a mechanism to combat the agricultural non-point source pollution through reducing the application of chemical fertilizer. Thus, farmers' GPB can promote green agricultural production development in the study area.

This study takes ASSs level as the independent variable and calculated the average expenditure of ASSs for one season of rice per mu in the village where smallholder farmers are located to measure the local development level of ASSs. Table 1 shows the dependant variable and it's definition. Compared with the availability indicators such as whether there are local ASSs, the average expenditure on ASSs can better represent the development level of ASSs.

Control variables in this study not only affect both ASSs and GPB but also differentiate smallholder farmers who use ASSs from non-users. A detailed description of the controlled variable and the variable definition is presented in Table 1. The study identified the individual characteristics of farmers (age, educational level, migrant work experience, and agricultural technology training experience), family characteristics (income level, family business type, and human capital), farmland characteristics (farmland area, the degree of farmland fragmentation, farmland levelling, and farmland fertility status), and village characteristics. The characteristics of the village mainly include the geographical location of the village and whether the local government has publicized agricultural green production policies in the village.

Diversity in ages, education status, work experience and agriculture technology training experience causes the difference in the supply and quality of agricultural labor in the rice production, and their perception of utilizing ASSs would also vary, therefore, the decision to use ASSs will be different among farmers. Family behaviour such as income level and family business type will directly affect the use of ASSs. Human capital indicates the

TABLE 3 Estimation results of the impact of ASSs on the GPB of smallholder farmers (ordinal probit model).

Variables	Model 1		Model 2	
	Soil testing formula fertilizer		Organic fertilizer	
	Coefficient	S.E	Coefficient	S.E.
ASSs	0.535**	0.259	0.653***	0.251
Age	−0.006	0.006	0.012**	0.006
Education level	0.031*	0.018	−0.015	0.018
Migrant work experience	0.002	0.009	0.005	0.008
Participate in technical training	0.098***	0.037	−0.182***	0.063
Income level	−0.017	0.042	0.046	0.041
Proportion of agricultural production income	−0.074	0.190	−0.197	0.195
Human capital	0.035	0.092	0.191**	0.089
Farmland area	0.017	0.018	0.013	0.018
Fragmentation degree of farmland	−0.006	0.034	0.001	0.036
Farmland levelling	−0.081	0.147	−0.282*	0.149
Farmland quality	0.036	0.067	0.200***	0.068
Geographic location	0.017	0.028	0.048*	0.028
Policy publicity	0.003	0.147	0.608***	0.133
Constant term	−3.580**	1.520	−6.039***	1.504
Number of samples	741		741	
p-value	0.0180		0.0000	

Note: *, **, *** indicate statistical significance at the level of 10%, 5%, and 1%, respectively.

number of college students in family members has effects on the use of ASSs. Since college students expected to have awareness and knowledge, households with college students will use more ASSs. College Students Going to the Countryside during Summer" is an annual event in China where college students promote green production policies and practices to small farmers. During this event, students provide education and support on sustainable agricultural practices such as the use of organic fertilizers and soil-tested formula fertilizers. The presence of college students can positively influence attitudes and behaviors towards green production among smallholders. By empowering small farmers to adopt sustainable practices, this initiative contributes to the long-term viability of their farms and supports larger societal goals of promoting environmentally-friendly practices and sustainable economic development. Additionally, the involvement of college students in promoting green production policies can bring attention to the importance of sustainability and contribute to its prioritization in decision-making.

The farmland endowment will create difference among smallholder farmers utilization behaviour of utilizing ASSs. Farmers with higher farmland endowment will have higher expenditure on purchasing ASSs. Farmland fragmentation has effect on the purchasing power of ASSs among smallholder farmers in that farmers with high degree of fragmented land spend less expenditure to purchase ASSs. The topography and quality of farmland also have effect on farmers ability of purchasing ASSs. Farmers who have fertile land will spend less to purchase ASSs than the counters. The geographical location of the village where smallholder farmers located has its own effect on the ASSs level. For instance, village with advanced infrastructure and near to urban area will purchase more ASSs than the counters because they will have other non-farm employment opportunities that provide additional income which improves their capacity of purchasing more ASSs. Farmers found in the villages with access to the government publicity of agricultural green production policies will have more information that enables them to have awareness to utilize ASSs.

4.2 Statistical analysis

Table 1 presents the definition and the descriptive statistics of variables used to examine the effect of ASSs on GAP of smallholder farmers. It can be seen that 21.2% of smallholder farmers in the study area have applied soil-tested formula fertilizer and 25.9% of smallholder farmers have applied organic fertilizer. This show that the overall proportion of smallholder farmers adopting the GPB is

TABLE 4 Estimation results of the influence of ASSs on the GPB of smallholder farmers (bivariate probit model).

Variables	Model 1		Model 2	
	Soil-tested formula fertilizer		Organic fertilizer	
	Coefficient	S.E.	Coefficient	S.E.
ASS	0.516**	0.258	0.641***	0.250
Age	−0.006	0.006	0.012*	0.006
Education level	0.032*	0.018	−0.014	0.018
Migrant work experience	0.002	0.008	0.005	0.008
Participate in technical training	0.099***	0.037	−0.188***	0.065
Income level	−0.016	0.042	0.049	0.041
Proportion of agricultural production income	−0.058	0.189	−0.168	0.195
Human capital	0.034	0.092	0.195***	0.089
Farmland area	0.017	0.018	0.012	0.018
Fragmentation degree of farmland	−0.006	0.034	−0.001	0.037
Farmland levelling	−0.076	0.146	−0.279*	0.149
Farmland quality	0.039	0.068	0.198***	0.068
Geographical location	0.016	0.027	0.048*	0.028
Policy publicity	−0.007	0.147	0.604***	0.133
Constant term	−3.511**	1.518	−5.996***	1.502
Number of samples	741			
p-value	0.0000			

Note: *, **, *** indicate statistical significance at the level of 10%, 5% and 1%, respectively.

still relatively low and has more place for improvement. The estimation result shows that in one season, the average expenditure of ASSs per mu in the village where smallholder farmers are located was 266.9 yuan. This shows that farmers use ASSs only for small proportion of rice production practices and in general the ASSs development level in the study area is low. The average age of farmers is 61.9 years, which shows that the rice production area is dominated by older farmers. Most of the respondents spend an average of 3.9 schooling years indicating that the respondents are completed only primary school. The average migrant work experience is 4.5 years.

Farmers have few training opportunities (0.43 times) and the total household income is 95, 230 yuan. The proportion of the average agricultural production income is 21.9%. Among the respondents, 21% of the household has at least one member of college student. The actual farmland area of households is 4.652 mu, which indicates that their land endowment is far lower than the national average and the average fragmentation degree of their farmland, which is calculated as number of plots/actual cultivated plots, is 1.288 block/mu, shows higher fragmentation rate. The majority of farmlands of the smallholder farmers is little slop (1.827). The average fertility status of the household in the study area is almost good (3.290). The average distance of farmers from the nears home town is 5.713 km. From the respondents, only a small proportion of respondents can access the government policy publicity (17.3%).

5 Results and discussion

5.1 Covariance matrix analysis

The covariance matrix results in Table 2 show that the correlation coefficient (ρ value) is 0.138, which is significant at the level of 1%, indicating that there is indeed a complementary effect between the application of soil testing formula fertilizer and organic fertilizer by smallholder farmers in the sample. Smallholder farmers applying organic fertilizer during rice planting are also more likely to apply soil-tested fertilizer, which is suitable for using the bivariate probit model.

5.2 The impact of ASSs on the GPB of smallholder farmers based on ordinal probit model

The ordinary probit model empirical analysis results of the impact of ASSs on the GPB of smallholder farmers are presented in Table 3. In Model 1, the impact of ASSs on the application of soil-tested formula fertilizer was presented, and the analysis was made based on the ordinary probit model. ASSs was used as an independent variable. The results show that the coefficient of ASS is 0.535 and significant at the 5% level, indicating that ASS

has a significant, positive impact on smallholder farmers' application of soil-tested formula fertilizer in rice production. Moreover, the coefficient of farmers' participation in technical training and education level are 0.098 and 0.031 and significant at 1% and 10%, respectively. This indicates that farmers' participation in various training and their education level has a significant positive effect on the GPBs smallholder farmers. In Model 2, the impact of ASSs on the application of organic fertilizer was presented. The analysis was made based on the ordinary probit model and ASSs was also used as an explanatory variable. The results show that the coefficient of ASSs is 0.653 and significant at the 1% level, indicating that ASS has a significant, positive impact on smallholder farmers' application of organic fertilizer in rice production. This finding is consistence with Epule et al., 2015, found that ASSs encourage smallholder farmers to participate in the agricultural green revolution paradigm. Moreover, age, human capital, farmland levelling, farmland quality, geographic location, and policy publicity have a significant positive impact on the application of organic fertilizer. Table 3 shows the estimation results of the ordinary probit model. From the point of view of the *p*-value, the overall estimation effect of the two models is relatively good and the model estimation results are robust.

5.3 The impact of ASSs on the GPB of smallholder farmers based on bivariat probit model

The bivariate probit model analysis results in Table 4 show that ASSs have a significant and positive impact on smallholder farmers' GPB, which confirmed the H1. In Model 1, the impact of ASSs on the application of soil-tested formula fertilizer was presented. The results show that the coefficient of ASS is 0.516 and significant at the 5% level, indicating that ASSs have a significant, positive impact on smallholder farmers' application of soil-tested formula fertilizer in rice production, which confirmed the H2. Moreover, the coefficient of farmers' participation in technical training and education level are 0.099 and 0.032 and significant at 1% and 10%, respectively. This indicates that farmers' participation in various training and with higher education levels has a significant positive effect on the GPB smallholder farmers. In Model 2, the impact of ASSs on the application of organic fertilizer was presented. The results show that the coefficient of ASS is 0.641 and significant at the 1% level, indicating that ASSs have a significant, positive impact on smallholder farmers' application of organic fertilizer in rice production, which confirmed the H2. Moreover, age, human capital, farmland levelling, farmland quality, geographic location, and policy publicity have a significant positive impact on the application of organic fertilizer.

Agricultural green production provides substantial benefits in the reduction of agricultural non-point source pollution (Liu et al., 2020). Smallholder farmers contribute to improving environmental quality by adopting green agricultural production practices. However, they cannot fully obtain the corresponding compensation. In most cases, rational smallholder farmers who struggle to survive to tend to avoid the risks by maintaining a high dosage of chemical fertilizers and pesticides to maximize the production profit. Thus, it is critical to provide a novel framework to harmonize farmers and environmental demand, refers to balancing the economic needs of smallholder farmers while protecting the environment. ASSs can significantly change farmers' factor input and agricultural production management mode. Moreover, ASSs assist farmers to purchase the standard agricultural input (such as soil-tested formula fertilizer and organic fertilizer) which was difficult to find in the normal market. The agricultural input delivered by ASSs is scientifically selected, realizes the input of pro-environment factors of production, and can be purchased at a reasonable price. Due to the large-scale procurement, ASSs organizations have stronger negotiation ability in the factor-input trading market. As a result, if smallholder farmers participate in ASSs, they can obtain a cheaper supply of production factors to effectively reduce production costs. In addition, ASSs organizations rely on the introduction of professionals and technical equipment to introduce the concept of green agricultural production into the process of agricultural production, to promote small farmers to think and make decisions on the green attribute of input factors.

Beside ASSs, the education level and participation in technical training have a significant positive impact on the application of soil testing formula fertilizer and organic fertilizer by smallholder farmers. Both education level and participation in technical training belong to knowledge-based variables. It can be seen that soil testing formula fertilizer is a knowledge-intensive agricultural production factor, because when soil testing formula fertilizer is applied, farmers need to understand the whole process of soil testing formula technology from field experiment to effect evaluation, and master the knowledge of fertilization time, fertilizer formula and fertilization methods in different growth periods of crops. Age, participation in technical training, human capital, cultivated land levelling, cultivated land quality, geographical location, policy publicity and other variables have a significant impact on the application of organic fertilizer by small farmers. Among them, age is positively correlated with the behavior of small farmers in applying organic fertilizer, indicating that older small farmers prefer to apply organic fertilizer. According to the actual investigation, older small farmers use some farm manure because of their original production habits and the opportunity to save the cost of applying chemical fertilizer. Older small farmers have rich farming experience and are more able to bear hardships.

On the contrary, smallholder farmers are more likely to use organic fertilizer. The variable of participating in technical training is negatively correlated with the behavior of small farmers applying organic fertilizer, which may be mainly because the technical training at the grass-roots level in the past emphasized the importance of modern production factors and had the goal orientation of increasing grain production; The change of human capital is positively related to the behavior of small farmers applying organic fertilizer. This paper uses the number of college students in the family as the measurement standard. College students are high-quality human capital in the family, which will enhance the green concept of the family and urge the family to adopt green production behavior. There is a negative correlation between cultivated land levelling and the behavior of small farmers applying organic fertilizer, which shows that the flatter the cultivated land is, the smaller farmers tend to apply organic fertilizer.

The high-standard farmland being vigorously promoted in China is conducive to encouraging small farmers to apply

organic fertilizer. The cultivated land quality variable is positively correlated with the behavior of smallholder farmers applying organic fertilizer. When the fertility of cultivated land is good, farmers tend to apply little organic fertilizer and *vice versa*. Farmers tend to use less organic fertilizer when the fertility of their land is high and more when it's poor. This may be due to a cost-saving perspective as excess fertilizer can result in a surplus of nutrients that may not be fully used by crops. Thus, to avoid waste, small farmers reduce the amount of fertilizer used when the fertility of their land is high. Conversely, increasing fertilizer application on low fertility land can replenish depleted nutrients and increase crop yield. Therefore, to increase yield, farmers tend to apply more fertilizer to lower fertility land. The geographical location variable is positively correlated with the behavior of small farmers applying organic fertilizer, indicating that the farther away from the nearest township government, the smaller farmers tend to apply organic fertilizer, which may be because the farther away from the market, the higher the cost of agricultural materials such as chemical fertilizer, which makes small farmers more willing to apply organic fertilizer such as farm fertilizer. The policy publicity variables are positively correlated with the behavior of small farmers applying organic fertilizer, indicating that small farmers who have heard the government's publicity of green production behavior in the villages are conducive to guiding small farmers to apply organic fertilizer.

In China, smallholder farmers will continue to play a pivotal role in the agricultural production sector. However, insufficient attention deteriorates the quality and the quality of their farming practices. In some cases, policies are biased to large farm holders and other agricultural entities than smallholder farmers. In particular, agricultural production services such as ASSs mainly subsidised and promoted to support large holder farmers which ignore smallholder farmers to involve in green agricultural production practices. Therefore, this study urges policymakers to pay proper attention for smallholder farmers through ASSs to improve the quality of their production such as adopting green agricultural inputs.

6 Conclusion and policy implications

Promoting the green development of agriculture is the bridge to realizing agricultural modernization and the trend of sustainable agricultural development in the future. Farmers' GPB such as the application of soil-tested formula fertilizer and organic fertilizer in rice production are crucial for the reduction of agriculture based environmental pollution. This study is based on the field survey data of 741 smallholder rice farmers in Hunan, Jiangxi, and Zhejiang provinces in China, using a probit model to determine the proportion of smallholder farmers who applied soil-tested formula fertilizer and organic fertilizer and the actual expenditure of smallholder farmers to purchase ASSs, studying the effect of ASSs utilization on the GPB, and to compare and discuss other factors effects on GPB of smallholder farmers. Based on the finding of this study, we draw the following conclusion:

First, the empirical analysis results revealed that at present, the proportion of smallholder farmers applying soil testing formula fertilizer and organic fertilizer in the rice production region of southern China is 21.2% and 25.9% respectively, indicating that the overall proportion is still relatively low. Second, ASSs can significantly promote the GPB of smallholder farmers. Third, the actual expenditures of ASSs influence smallholder farmers to apply soil testing formula fertilizer and organic fertilizer. The higher the price of ASSs, the more farmers tend to reduce the application of soil testing formula fertilizer and organic fertilizer which negatively affects the GPB of smallholder farmers.

To create an organic connection between smallholder farmers and modern agricultural development and further enhance the participation of smallholder farmers in green agricultural production, this study insights the following policy recommendations:

Several policy recommendations and constructive solutions can be suggested based on the findings of this study. Firstly, to increase the coverage of agricultural socialized services (ASSs), policymakers can consider expanding the funding support for these services or incentivizing agricultural service providers to offer services to more smallholder farmers in the southern China region. This could potentially enhance the GPB of smallholder farmers, as the study found that ASSs have a significant and positive impact on GPB. Secondly, policymakers can increase the awareness of green production practices among smallholder farmers through training and capacity-building programs. This could promote the adoption of green production practices and improve agricultural productivity, as the study found that farmers who obtained ASSs tend to apply organic and soil-tested fertilizers more frequently than those who did not.

Thirdly, optimizing the public administration service system could further strengthen ASSs. By streamlining administrative procedures and providing more efficient and effective services to agricultural producers, policymakers could improve the delivery of ASSs and enhance their impact on smallholder farmers' GPB. Fourthly, establishing a joint service organization could also strengthen ASSs. Setting up a platform for different stakeholders to collaborate and coordinate their efforts in promoting GPB among smallholder farmers could facilitate the sharing of knowledge, expertise, and resources, and promote the integration of different types of ASSs. Lastly, creating a good financial and legal service environment could strengthen ASSs by providing financial incentives and legal protections for agricultural service providers who offer ASSs to smallholder farmers. This could encourage more providers to offer ASSs and ensure their sustainability and effectiveness over time. In summary, policymakers could consider implementing these policy recommendations and solutions to promote the adoption of green production practices and enhance the GPB of smallholder farmers in southern China.

Despite the contributions of this study to the field, there are some limitations that should be acknowledged. Firstly, the sample size used in this study is relatively small as it was conducted only in three provinces in southern China. Therefore, it may not be sufficient to generalize the results to other regions or even other countries. Secondly, the study only focused on the impact of ASSs on fertilization behavior, but did not examine other green production behaviors of smallholder farmers. Future studies can expand the analysis to other behaviors such as irrigation, pest management, and harvesting. Finally, the study only examined the impact of ASSs from the

perspective of smallholder farmers, but did not investigate the perspectives of other stakeholders such as government agencies, agricultural service providers, and consumers. Thus, a more comprehensive investigation is needed to understand the effectiveness of ASSs in promoting GBP.

This study opens up several avenues for future research. Firstly, future studies can expand the investigation to include other regions in China or even other countries to enhance the generalizability of the findings. Secondly, future research can focus on other green production behaviors beyond fertilization to provide a more comprehensive understanding of the effectiveness of ASSs. Thirdly, future research can examine the perspectives of various stakeholders and explore the interplay between them to provide a more holistic view of the impact of ASSs on GBP. Fourthly, future research can employ other statistical models beyond the probit model used in this study to provide more robust evidence. Finally, future research can explore the use of emerging technologies such as artificial intelligence and blockchain to enhance the effectiveness of ASSs in promoting GBP.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

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Conflict of interest

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Does the disclosure of medical insurance information affect patients' willingness to adopt the diagnosis related groups system

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Introduction: Medical insurance information disclosure is not only a direct way for the public to understand and master social insurance information and resource use benefits, but also an important way for the public to participate in medical service governance and supervision. Some studies have shown that information disclosure can significantly reduce the risk perception of user groups, strengthen their trust and reduce the negative impact of information asymmetry.

Methods: Based on risk perception and trust perception theories, this paper focuses on the mechanisms influencing patients' attitudes in the process of implementing a Diagnosis Related Groups payment system. Using medical insurance information disclosure from a governance perspective as the research object, the impact of medical insurance information disclosure on patients' willingness to adopt the Diagnosis Related Groups payment system was analyzed by means of a questionnaire survey, Data analysis and hypothesis testing *via* SPSS while the mechanism of the impact of medical insurance information disclosure on patients' attitudes was explored in depth.

Results: It was found that medical insurance information disclosure had a significant positive effect on patients' trust perceptions and a significant negative effect on patients' risk perceptions. The more comprehensive information patients received, the stronger their trust and the lower their perceived risk.

Discussion: This paper conducts an empirical study from patients' perspective, broadens the scope of research on medical insurance Diagnosis related groups, enriches the application of risk perception and trust perception theories in the medical field, and provides management suggestions for medical institutions in the management of medical insurance information disclosure.

KEYWORDS

medical insurance information, DRG, patients' willingness, risk perception, trust perception

1. Introduction

The world's population is aging rapidly. The World Health Organization says the world's population over 60 will double to 2.1 billion people by 2050. In China, the older adult population is expected to grow to 366 million by 2050, with the proportion of the older adult population rising to 26.1 percent (1). All countries are facing the major challenge of population aging, and organizations are actively exploring new programs to address this demographic shift. The aging

of population has brought great economic burden to the society at the same time, it also brings great challenges in the aspects of medical insurance (2). Compared with younger groups, the older adult have reduced immune function and often suffer from various chronic diseases, which puts great economic pressure on families and society and seriously affects their quality of life (3). As the number of older adult population increases year by year, the demand for medical services and resources also increases (4). Rising health care expenditures place a heavy financial burden on individual patients and national health insurance plans. In China, this burden is largely caused by the previous payment system (5). In the past, payment by service item and other medical insurance payment methods generally believe that the higher the price, the better the quality of services, leading to the unreasonable increase of medical insurance fund expenditure, resulting in the waste of medical insurance fund (6). Therefore, it is urgent to strengthen the reform of medical insurance payment and provide quality medical services for medical insurance enrollees, especially older adult enrollees (7). In November 2021, the National Medical Insurance Administration issued the "Three-Year Action Plan for the Reform of Diagnosis related groups (DRG) Payment Method," which clarified that "after the overall planning area starts the DRG (Diagnosis Related Groups, payment based on disease diagnosis-related groups) payment reform work, the DRG payment medical insurance fund expenditure will be realized according to the three-year arrangement (8). This is accounting for the goal of reaching 70% of the hospitalization medical insurance fund expenditure in the overall planning area (9).

Diagnosis related groups were derived from the reform of the health care expenditure system in the United States in the 1980s, and have gradually been used worldwide (10). DRG payment is currently recognized as one of the most effective and scientific medical insurance payment methods in the world (11). As of October 2022, DRG actual payment in 30 pilot cities has covered 807 medical institutions, and the coverage rate of tertiary hospitals has reached 57.4% (12). DRG payment is the core of medical insurance payment reform, an important measure to deepen the reform of the medical system and has far-reaching significance for balancing the quality of medical services and the use of medical insurance funds (13). The implementation of the DRG payment system means that the living environment of public hospitals is undergoing profound changes, which brings great uncertainty to the industry competition they face (14). It will comprehensively improve medical quality, implement refined management, and strengthen risk management (15). New requirements and challenges have been raised. The most important role played by the DRG medical insurance reform is to provide scientific basis for the analysis and evaluation of the cost, performance and quality of medical services, help patients understand the corresponding medical service process of the hospital, strengthen supervision, and realize the transparency of medical service management (16).

At present, although there are a large number of literatures to study the willingness of medical personnel and management departments to adopt and use the DRG medical payment system (17). However, there is no literature on the willingness of medical insurance users and patients to adopt the DRG medical payment system and explore its influencing factors on their willingness to adopt. Compared with the existing literature, this study will conduct an in-depth study on the attitude and willingness to adopt the DRG medical payment system from the perspective of patients. The patient's willingness and attitude to use play an important role in the successful promotion and use of the DRG medical payment system.

After research, trust and risk perception are important factors that affect patients' willingness to comply with and adopt the DRG payment system. Therefore, it is of great practical significance to explore the reasons for the low willingness of patients to adopt the DRG payment system and seek effective measures to increase the willingness of patients to adopt the DRG payment system. However, in countries that have adopted DRG for payment, there are also characteristics of poor health insurance information disclosure, DRG has changed the behavior and habits of patients, making patients do not understand the existing health insurance system, resulting in information asymmetry (18). Previous studies have shown that information disclosure can increase public trust and reduce public risk perception. Under the framework of modern medical governance, the disclosure and transparency of medical insurance information will help patients know the source and whereabouts of medical income and expenditure, and facilitate the supervision of hospital behavior by patients and medical insurance users, which is conducive to standardizing hospital medical behavior and enhancing patients' confidence. Trust and reduce risk perception of patients. In a highly regulated medical environment, patients are more inclined to adopt the highly secure DRG payment system. As a relatively scientific and rational method of medical cost management and quality evaluation, DRG is a medical management tool, and the most important thing is to realize the win–win situation of medical insurance and patients in hospital management practice (19). However, patient groups are not concerned about this new health care model. The asymmetry of information may lead to the fact that patients will not easily choose the new health insurance payment model. For this reason, this study from the perspective of medical insurance information disclosure and medical insurance information transparency, it is an important measure to deepen the reform of the medical system to investigate the factors that affect the willingness of patients to adopt the DRG payment system, and to explore effective ways to improve the adoption of the DRG payment system by medical insurance users and patients in my country. It is of far-reaching significance to balance the quality of medical services and the use of medical insurance funds.

2. Literature review and research hypothesis

2.1. Diagnosis related groups

Diagnosis related groups (DRG) is a system that divides patients into multiple diagnostic groups for management based on their age, diagnosis, complications and complications, severity of disease, treatment and outcome, and resource consumption. It is an important means to establish a new operation compensation mechanism for public hospitals, improve the problem of unreasonable increase of medical costs, gradually promote hierarchical diagnosis and treatment, promote the transformation of service mode, and finally realize a win–win situation among medical insurance and patients. Previous studies on DRGS mostly focused on the analysis of DRG

TABLE 1 Diagnosis related groups literature review.

References	Research perspective	Research variable	Conclusion
(20)	DRG	Medical services are the main influencing factors	The DEMATEL method is used to identify the factors affecting the overall performance of medical service, and it is suggested to pay attention to the ability of medical service providers when selecting or using DRG
(21)	patient	Composition of medical expenditure	Based on the decision tree model, the process of hospitalization, surgery, diagnosis and treatment of colorectal cancer patients is managed, reducing the financial burden of patients
(22)	patient	Hospital caseload	Inpatient medical costs and average length of stay vary significantly in hospital concentration index, and the extension of DRG payment system to hospitals will negatively impact their total sales
(23)	DRG	Intensive care and nursing services	The shortage of qualified intensive care nurses and doctors is the biggest threat to intensive care and recommendations are made to address this problem
(24)	DRG	DRG costs	LM is a superior method to detect both low and high outliers for DRG costs, thereby improving the efficiency and effectiveness of DRG prospective payment systems and equity of healthcare
(25)	doctor	Medical practice	The implementation of DRGS has transformed medical practice into a process of cost-effectiveness optimization
Our research	patient	Disclosure of medical insurance information, willingness to adopt	Trust and risk perception are important factors affecting patients' willingness to comply with the adoption of DRG payment system

It can be found that few scholars discuss the DRG system from the perspective of patients. Therefore, this study analyzes the DRG system from the perspective of patients, trying to broaden the scope of research in this field.

payment policy itself and its impact on medical institutions and medical services. Table 1 provides a summary of the existing literature on DRG payment systems.

2.2. Disclosure of medical insurance information

Information disclosure refers to the system in which an organization actively discloses information to the public or to specific individuals or organizations through certain forms and procedures in the course of daily operations (26). Similar expressions include "information disclosure," "information transparency," etc. "Wait. The "Guiding Opinions on Actively Promoting the Reform of Medical Care, Medical Insurance, and Medical Linkage" pointed out that the reform of the medical and health system should be deepened, the medical care, medical insurance, and medical linkage should be implemented, and the role of medical insurance in medical reform should be fully utilized (27). In order to better play the role of medical insurance in the medical reform, it is necessary to let the public understand the medical insurance policy (28). The disclosure of medical insurance information by hospitals is an important way for the public to obtain information (29). The disclosure of hospital medical insurance information can let the public understand the medical insurance policy and help the public make reasonable decisions when seeking medical treatment (30). The disclosure of medical insurance service information can allow the public to enjoy medical insurance benefits conveniently and improve the public's medical experience (31). At the same time, the disclosure of medical insurance information can increase the trust of patients and reduce the risk perception of patients to the hospital (32). Therefore, hospital administrators should pay attention to the disclosure of medical insurance information (33).

With the rapid development of Internet information technology, the disclosure of medical insurance information will be an important part of the reform of my country's medical and health services, and an important starting point for the government to supervise hospitals (34). It is an important guarantee for patients to trust medical institutions (19). The health administrative department should formulate corresponding policy documents to clarify the specific requirements for hospital medical insurance information disclosure, so that hospitals follow a unified disclosure standard, and at the same time strengthen the supervision of information disclosure, and increase the motivation of hospitals to disclose information (35). In 2022, a survey of the "National People's Trusted Model Hospital" announced by the Chinese Hospital Association found that 51.5% of the official websites of hospitals disclosed medical insurance policies, and 22.7% of the official websites of hospitals disclosed medical insurance details (36). Hospital medical insurance information disclosure is an important way for the public to obtain medical insurance information, and incomplete public information is not conducive to the public's comprehensive understanding of medical insurance policies and services. In order to provide patients with better medical insurance services and medical experience, hospitals need to disclose complete medical insurance information and make medical insurance information transparent (37). The disclosure of medical insurance information will also affect patients' trust in wishes and risk perception.

2.3. Trust perception theory

Trust Perception Theory is a theory that studies how people generate and perceive trust and mistrust, and it emphasizes the process of perceptual and cognitive interactions between individuals. The theory argues that the interaction between individuals and their

environment can lead individuals to develop trust, and at the same time, specific environments can change their trust perceptions (38). Trust is a complex psychosocial phenomenon that involves multiple dimensions and dimensions. Wang Menghan considers trust as an attitude that someone's behavior or the order around them is in accordance with his or her wishes, and believes that the technical competence of a certain person is one of the important factors affecting trust (30).

The doctor–patient relationship is the most fundamental social relationship in health care (39). For a long time, the frequent occurrence of doctor-patient disputes has led to the deterioration of the doctor-patient relationship, which has caused widespread concern in the society (35). The doctor-patient disputes have brought serious negative impacts to the health care system, causing both hospitals and patients to fall into the "access paradox trap." The root cause of doctor-patient conflict is lack of trust (40). According to Powell, "trust can be used to solve complex practical problems more quickly and with less effort than using authority to limit or use predictions and other methods." The degree of transparency of health care providers' information about health care is an important factor that influences residents' trust in hospitals (41) Chunnian and Lingyu (38) identified medical information disclosure as an important factor influencing doctor-patient trust. Jinshu et al. considered hospital disclosure of health care information as an important factor influencing patients' willingness to receive follow-up services and cooperation from hospitals (42). In the doctor–patient relationship, a higher level of patient trust in the hospital can help doctors carry out better clinical treatment and increase patients' sense of security, which is especially important for patients' active cooperation and disease recovery (43). Patients must first trust the hospital in order to actively cooperate with it and cooperate with the relevant policies introduced by the hospital (32). Several studies have found that patients generally have a pre-determined distrust of hospitals (44). This mistrust exists before the actual effective communication and information interaction between the doctor and patient, which affects the interests of both the doctor and the patient.

2.4. Risk perception theory

Currently, there are two relatively well-established theories for the study of risk perception, namely risk culture theory and risk psychometric theory (45). The school of risk culture theory, led by Douglas, defines the degree of risk perception of individuals mainly through common cultural communication (37). Different individuals have different risk perceptions in the face of different environments and cultures. The school of risk psychometrics led by Slovic mainly uses psychological knowledge to measure individual risk perceptions and uses psychometric paradigms to measure individual risk perceptions (46). Risk perception theory studies people's subjective psychological feelings from an individual perspective (47). Through the limited rational behavior people exhibit, it is reasonable to expect people's perceived assessment and perception of risk in different environments and scenarios, and what risky decisions people will make (35). Since then, with the continuous development of risk theory, many scholars have extended the concept of risk perception to various degrees (48). Bauer understands risk perception as the inability of consumers to accurately identify the good or bad of their behavioral decisions, which leads to uncertainty about the outcome (49). Slovic (50) formulated risk perception as an individual's judgment of risk given limited or uncertain knowledge of the information environment.

Risk perception theory emphasizes the importance of people's subjective perceptions of risk and their perceptions of the environment. It has been applied in many fields, such as health, finance and environmental issues, to help people more accurately assess possible risks and make more informed decisions. In healthcare, there is a relationship between patients' risk perception and patients' behavioral decisions (51). In studying the influence of risk perception on patients' behavioral decisions to enroll in insurance, Sun Jiaxin et al. (52) focused on patients' risk perceptions of hospitals. It was found that the lower the patients' risk perception of the hospital, the more patients participated in hospital decision making and actively cooperated with hospital medical behaviors.

2.5. Willingness to adopt

Yang Weizhong (49) found that patients' risk perception level and patients' trust in the hospital have an important impact on whether patients actively cooperate with the hospital. Chen Xinjian and Wei Yuanyuan (53) combined field survey data and used empirical analysis methods to study the risk management strategies perceived by hospital patients. The research results showed that there was a significant inverse relationship between patients' risk perception level and the degree of hospital information disclosure. Xue Wentian's (54) study found that patients' risk perception is low, and the higher the trust level, the stronger the patient's willingness to actively cooperate with the hospital and take hospital-related measures.

In this study, patients' willingness to adopt the DRG payment system is mainly affected by two factors: patients' trust and risk perception. The higher the patient's trust in the hospital, the stronger the patient's willingness to adopt the DRG payment system. The stronger the risk perception felt by the patient, the lower the patient's willingness to adopt the DRG payment system.

2.6. Research hypothesis

The disclosure of medical insurance information can make the whole process of medical institutions from management, operation to service open and transparent, so as to improve the supervision of the public and improve the quality of their medical services (55). Some scholars have pointed out that the information disclosure content, channels and effects of an organization have a positive impact on the trust of the organization (50). If the organization discloses false information or the information disclosed is incomplete, it will cause public distrust of the organization. Another study pointed out that the imbalance between the supply and demand of medical service information is the key reason for the lack of mutual trust between doctors and patients in recent years (56). Strengthening the disclosure of medical service information to meet the information needs of patients can reduce the degree of information asymmetry between doctors and patients and reshape the mutual trust between doctors and patients (57). In addition, Xiaokang et al. (47) and others explored the cognitive mechanism of individuals' perception of medical information

risk based on the theory of empirical analysis and processing and word-for-word processing. Therefore, this study hypothesizes:

> *H1*: Medical insurance information disclosure can improve patients' trust perception.
>
> *H2*: Medical insurance information disclosure can reduce patients' risk perception.

In terms of risk perception, Chunnian and Lingyu (58) found through empirical research that user perceived risk has a direct impact on user experience and continuous use intention of emergency website information services, and Ruixian and Mengjun (59) found that user perceived risk will significantly affect social software users. Yanan and Chaohua (60) found that perceived financial risk and perceived time risk are the main variables that affect user satisfaction and continued use intention through the user satisfaction of online medical and health websites. Sun et al. (61) also explored the direct effect of risk perception on usage behavior. The studies of the above scholars all reflect that risk perception affects users' willingness to use to a certain extent. Secondly, in terms of trust perception, Mengxuan and Weihua (28) built a model of factors influencing public willingness to use Internet medical service platforms based on trust theory, and verified through analysis that trust has a direct and positive impact on public willingness to use. Yanan & Chaohua (62) constructed a relationship model between the quality of government electronic information services and the public's willingness to continue to use, pointing out that perceived trust can have a positive impact on the willingness to continue to use. The research of the above scholars reflects that trust perception affects users' willingness to use to a certain extent. Based on this, in order to explore the influencing factors of patients' willingness to adopt DRG, this study focuses on the internal perception state of patients, and puts forward the hypothesis:

> *H3*: Improving patients' trust perception is conducive to improving patients' willingness to adopt DRG.
>
> *H4*: Reducing the risk perception of patients is conducive to improving patients' willingness to adopt DRG.

As shown in Figure 1, the theoretical model proposed in this study assumes that the disclosure of medical insurance information will increase patients' trust perception, reduce patients' risk perception, and then increase patients' willingness to adopt DRG.

3. Data and method

3.1. Scale design

On the basis of referring to the existing research, combined with the development status of medical insurance DRG payment, this study improved the relevant scales and designed a questionnaire on the willingness of medical patients to adopt the medical insurance DRG system. The questionnaire is mainly composed of two parts, the first part is the basic information of the patient, and the second part is factor analysis, which is set as a scale question and selected as a five-point Likert scale to measure, 1 means strongly disagree and 5 means strongly agree. The measurement of medical insurance information disclosure mainly refers to the research of Xuan and Xuefen (63) and others on the current situation of medical security information network disclosure; the risk perception scale is relatively mature, mainly referring to the influencing factors of risk perception of public health emergencies such as Xie Mengya (64) Research; the measurement of trust perception refers to the research of Mengzhen and Peng (53) and others; the design of the adoption willingness scale mainly refers to the research of scholars on the willingness to use. The specific questionnaire items for each variable are shown in Table 2. Participants who complete the survey will receive a random cash reward to encourage active participation.

3.2. Data collection

Based on the research object and content of this paper, the questionnaire is mainly distributed to patients who have used the medical insurance DRG payment method. From December 20, 2022 to December 30, 2022, the questionnaire is distributed through online channels in the form of online survey. We use the online survey tool Questionnaire to distribute surveys and collect data. Questionnaire Star is the largest professional survey platform in China, with more than 1 million respondents filling out the questionnaire every day, ensuring the integrity and authenticity of the collected information. It specifies a variety of sample attributes such as gender, age, region, occupation, industry, etc., to accurately locate the target group. In addition, various filtering rules, filtering pages, quota control and other conditions can be set, and manual troubleshooting is supported to ensure the validity of its data (65). At the same time, more samples were collected by means of snowball, and 260 valid questionnaires were finally collected (Questionnaire link: https://www.wjx.cn/vm/wo3vFFD.aspx).

Table 3 lists the descriptive analysis of the basic information of the samples. Among the effective samples, male samples accounted for 53.1%, female samples accounted for 46.9%, and the gender composition of the samples was relatively balanced. In terms of age, most of the patients in the sample were 18–30 years old, and the rest of the age groups were evenly distributed. In terms of academic qualifications, undergraduate education accounted for a large proportion, reaching 43.5%. There are many enterprise employees in the sample, accounting for 42.7%. The average monthly income is mostly concentrated in 4,000 ~ 6,000 yuan. In terms of payment methods, only 8.1% of the samples chose to pay at their own expense, indicating that the samples should have a certain degree of understanding of medical insurance payment, which improved the reliability of this survey.

4. Empirical analysis and results

4.1. Reliability and validity analysis

In this study, SPSS and AMOS software were used to conduct confirmatory factor analysis to evaluate the reliability and validity of the scale. Previous academic research has found that when the Cronbach's

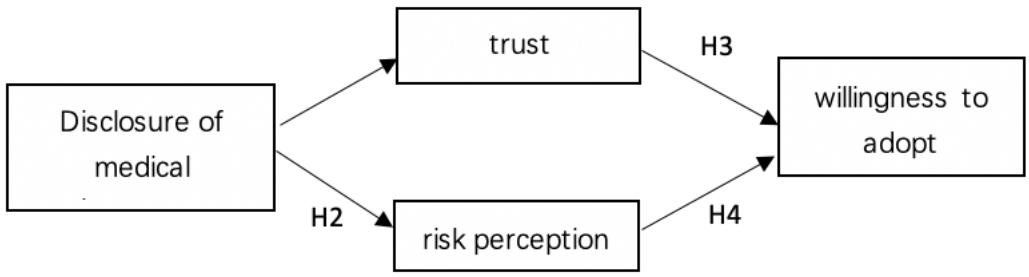

FIGURE 1
Framework diagram of theoretical model.

TABLE 2 Scale design and sources.

Constructs	Item	Source
Medical insurance information disclosure	I understand the disclosure of medical insurance information	(63)
	I know the methods of medical insurance payment	
	I know what DRG is	
	I know the specific items and scope of medicare reimbursement	
	I understand the fee criteria for each diagnostic-related group	
	I know the medicare process	
	I know the percentage and amount of reimbursement	
Risk perception	I'm concerned about the loss of property due to the lack of transparency of health insurance information	(64)
	I'm concerned about excessive monetary losses due to inaccurate group billing	
	I worry that DRG, a new payment system, is not yet mature	
	I'm worried that DRG-related irregularities will lead to medical disputes	
	I'm concerned that DRG is not objective and reasonable in its costing	
	I'm concerned that DRG does not have enough supervision when paying to reduce the burden	
Trust perception	I think the DRG payment system will save costs	(53)
	I think paying with DRG is more reliable than other payment methods	
	I think the privacy on the DRG payment system is well protected	
	I think it is safe to visit a hospital using the DRG payment system	
	I believe that DRG can standardize medical services and make the medical process more standardized and reliable	
	I think DRG payments ensure that every Medicare fund is spent on the cutting edge	
Willingness to adopt	I accept the DRG payment system	(35)
	I would like to know more about DRG's payment system	
	I plan to visit a hospital later at a hospital that I paid for using DRG	
	I think there are many benefits to using the DRG payment system	
	I would like to introduce the medical insurance DRG payment system to my friends	

alpha coefficient of each variable in the model exceeds 0.7 (66), and the combined reliability (CR) is also greater than 0.7, the model meets the reliability test (61). In the confirmatory analysis results in Table 4, the Cronbach's alpha coefficients of medical insurance information disclosure, risk perception, trust perception and willingness to adopt all exceed 0.7. In addition, the combined reliability (CR) of each variable is greater than 0.7, and the model meets the reliability test.

According to previous studies, if the standardized factor loading exceeds 0.70 and the average variance extraction (AVE) is greater than 0.50, the model meets convergent validity (46, 47). In Table 3, the loads of each standardized factor are between 0.741 and 0.995, all greater than 0.70, and the average variance is also between 0.621 and 0.882, all greater than 0.50. The model supports convergent validity.

4.2. Correlation analysis and regression analysis

4.2.1. Correlation analysis

This paper mainly analyzes the correlation between medical insurance information disclosure, risk perception, trust perception and adoption willingness, which lays the foundation for further research. The relevant analysis results are shown in Table 5 below.

Correlation analysis is to analyze the degree of correlation between various variables studied. In this paper, SPSS 26.0 is used for correlation analysis, and the results are shown in Table 5 (67). Correlation analysis is firstly to verify whether there is correlation between variables, and secondly to examine the degree of correlation between variables. In studies, Pearson correlation coefficient is usually used to describe the degree of correlation. When the absolute value is 0.8–1.0, it can be considered that there is a strong correlation between variables. When the absolute value is 0.6–0.8, it can be considered that there is a strong correlation between variables. When the absolute value is 0.4–0.6, it can be considered that there is a moderate degree of correlation between variables. When the absolute value is 0.2–0.4, it can be considered that there is a weak correlation between variables. When the absolute value is between 0.0 and 0.2, the correlation between variables can be considered to be very weak or no correlation (68).

It can be seen from Table 5 that there is a significant negative correlation between medical insurance information disclosure and risk perception ($r=-0.636^{**}$, $p<0.05$); medical insurance information disclosure and trust perception ($r=0.749^{**}$, $p<0.05$), it has Significantly positive correlation; Risk perception has a significant negative correlation with adoption intention ($r=-0.376^{**}$, $p<0.05$); Trust perception has a significant positive correlation with adoption intention ($r=0.782^{**}$, $p<0.05$). Other demographic variables had no or very weak correlation with the study variables.

4.2.2. Regression analysis

It can be seen from Table 6 above that the linear regression analysis takes medical insurance information disclosure as an independent variable and trust perception as a dependent variable, and the regression coefficient value of medical insurance information disclosure is 0.678 ($t=18.153$, $p=0.000<0.01$), which means The disclosure of medical insurance information will have a significant positive impact on trust perception, assuming that H1 is established.

It can be seen from Table 7 above that the linear regression analysis is performed with medical insurance information disclosure as an independent variable and risk perception as a dependent variable, and the regression coefficient value of medical insurance information disclosure is-0.519 ($t=-13.236$, $p=0.000<0.01$), It means that the disclosure of medical insurance information will have a significant negative impact on risk perception, and the hypothesis H2 is established.

From Table 8 above, it can be seen that using trust perception as an independent variable and adopting willingness as a dependent variable for linear regression analysis, the regression coefficient value of trust perception is 0.779 ($t=20.146$, $p=0.000<0.01$), which means that trust perception Will have a significant positive impact on the willingness to adopt, assuming that H3 is established.

It can be seen from Table 9 above that the risk perception is used as an independent variable, and the willingness to adopt is used as a dependent variable for linear regression analysis, and the regression coefficient value of risk perception is −0.416 ($t=-6.519$, $p=0.000<0.01$), which means Risk perception will have a significant negative impact on adoption willingness, and hypothesis H4 is established. Finally, the obtained model results are shown in Figure 2.

TABLE 3 Basic information descriptive analysis.

Characteristic	Categorization	Frequency	Percent
Gender	Male	138	53.1%
	Female	122	46.9%
Age	18–25 years old	78	30.0%
	26–30 years old	70	26.9%
	31–40 years old	38	14.6%
	41–50 years old	40	15.4%
	51–60 years old	32	12.3%
	Over 60 years	2	0.8%
Education level	High school and below	36	13.8%
	Associate degree	79	30.4%
	Undergraduate	113	43.5%
	Master's degree and higher	32	12.3%
Career	Government agencies, Institutions	81	31.2%
	Enterprise employee	111	42.7%
	Individual business	39	15.0%
	Farmer	26	10.0%
	Student	3	1.2%
Average monthly income	Below 4,000 yuan	82	31.5%
	4,000–6,000 yuan	108	41.5%
	6,000–8,000 yuan	29	11.2%
	8,000–10,000 yuan	34	13.1%
	More than 10,000 yuan	7	2.7%
Payment method	Medical insurance for urban workers	83	31.9%
	Medical insurance for urban residents	84	32.3%
	New rural cooperative medical care	42	16.2%
	Commercial insurance	30	11.5%
	Own expense	21	8.1%

4.3. Discussion

In summary, unlike previous scholars who mostly focused on the willingness of medical staff or management to adopt and use the DRG medical payment system, this study conducted an in-depth study from

TABLE 4 Confirmatory analysis results.

Variable	Code	Cronbach's alpha	CR	AVE	Standard load	S.E.
Medical insurance information disclosure	Q7	0.964	0.964	0.795	0.880	–
	Q8				0.856	0.108
	Q9				0.904	0.106
	Q10				0.874	0.109
	Q11				0.929	0.106
	Q12				0.908	0.104
	Q13				0.888	0.105
Risk perception	Q14	0.977	0.978	0.882	0.995	–
	Q15				0.909	0.038
	Q16				0.940	0.033
	Q17				0.933	0.035
	Q18				0.946	0.032
	Q19				0.908	0.039
Trust perception	Q20	0.907	0.908	0.621	0.835	–
	Q21				0.802	0.091
	Q22				0.803	0.091
	Q23				0.741	0.096
	Q24				0.775	0.091
	Q25				0.769	0.103
Willingness to adopt	Q26	0.902	0.903	0.650	0.815	–
	Q27				0.851	0.092
	Q28				0.784	0.090
	Q29				0.775	0.089
	Q30				0.805	0.093

$\chi^2/df = 2.640$; RMSEA = 0.08; NFI = 0.913; IFI = 0.944; CFI = 0.944.

TABLE 5 Correlation analysis.

	Variable	1	2	3	4	5	6	7	8	9	10
1	Gender	1									
2	Age	0.145	1								
3	Education level	0.165	−0.031	1							
4	Career	−0.094	0.074	0.084	1						
5	Average monthly income	−0.163*	−0.068	0.200	−0.002	1					
6	Payment method	−0.034	0.027	−0.009	−0.075	−0.151	1				
7	Medical insurance information disclosure	0.037	−0.006	−0.147	0.167	0.004	−0.043	1			
8	Risk perception	0.003	0.101	0.107	−0.028	0.022	0.024	−0.636**	1		
9	Trust perception	−0.004	−0.061	−0.103	0.136	0.053	−0.037	0.749**	−0.394**	1	
10	Willingness to adopt	−0.052	−0.031	−0.025	0.156	0.029	−0.043	0.626**	−0.376**	0.782**	1

TABLE 6 Regression analysis of medical insurance information disclosure on trust perception.

	Non standardized coefficient B	Standardization coefficient beta	*t*	*p*	VIF
Constant	1.131	–	7.570	0.000**	–
Medical insurance information disclosure	0.678	0.749	18.153	0.000**	1.000
R^2		0.561			
Adjusted R^2		0.559			
F		$F = 329.517$, $p = 0.000$			
D–W value		2.727			

TABLE 7 Regression analysis of medical insurance information disclosure on risk perception.

	Non standardized coefficient B	Standardization coefficient beta	*t*	*p*	VIF
Constant	4.716	–	30.069	0.000**	–
Medical insurance information disclosure	−0.519	−0.636	−13.236	0.000**	1.000
R^2		0.404			
Adjusted R^2		0.402			
F		$F = 175.204$, $p = 0.000$			
D–W value		2.025			

TABLE 8 Regression analysis of trust perception on adoption willingness.

	Nonstandardized coefficient B	Standardization coefficient Beta	*t*	*p*	VIF
Constant	0.905	–	6.050	0.000**	–
Trust perception	0.779	0.782	20.146	0.000**	1.000
R^2		0.611			
Adjusted R^2		0.610			
F		$F = 405.878$, $p = 0.000$			
D–W value		2.296			

TABLE 9 Regression analysis of risk perception on adoption willingness.

	Non standardized coefficient B	Standardization coefficient beta	*t*	*p*	VIF
Constant	4.946	–	27.059	0.000**	–
Risk perception	−0.416	−0.376	−6.519	0.000**	1.000
R^2		0.141			
Adjusted R^2		0.138			
F		$F = 42.491$, $p = 0.000$			
D–W value		2.040			

the patient's perspective, while paying attention to the current situation of inadequate information disclosure about the medical insurance system, and explored the relationship between medical insurance information disclosure, risk perception, trust perception and patients' willingness to adopt DRG through SPSS empirical analysis based on survey data and relevant theories (69). According to the empirical analysis results, all hypotheses have been effectively verified. Firstly, medical insurance information disclosure has a significant positive impact on patients' perception of trust and a significant negative impact on patients' perception of risk. The more

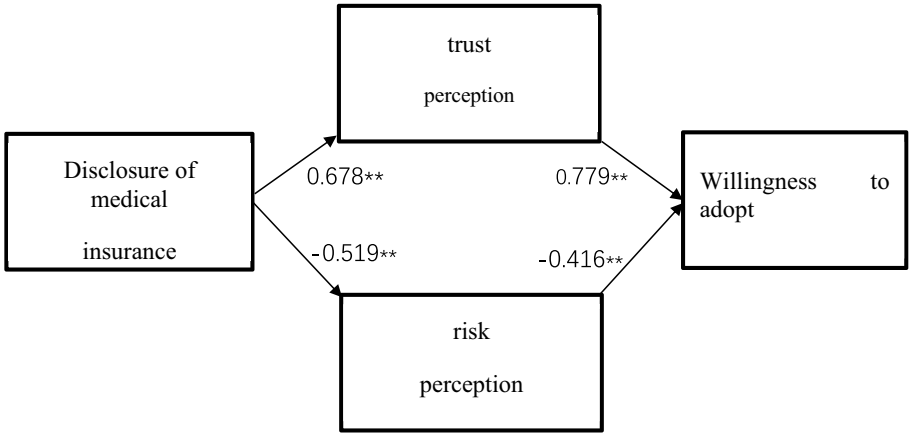

FIGURE 2
Model result graph.

comprehensive the information patients have, the stronger their sense of trust will be and the lower their perceived risk will be. In other words, medical insurance information disclosure can improve patients' perception of trust and reduce their perception of risk. Secondly, patients' perception of trust has a significant positive impact on their willingness to adopt DRG, while patients' perception of risk has a significant negative impact on their willingness to adopt DRG. Improving patients' perception of trust or reducing patients' perception of risk is conducive to improving patients' willingness to adopt DRG (70).

5. Conclusion

This study found that medical insurance information disclosure can improve patients' trust, reduce patients' risk perceptions, and increase patients' willingness to adopt DRGS. In practical application, the healthcare industry should use various social media to publicize the DRG payment policy and increase the publicity to make patients understand the DRG payment policy (52). In hospital management, hospital managers need to pay attention to the data needs of DRG grouping, organize and count the data sources of DRG grouping, and establish a good DRG-specific database, so as to improve the professionalism and scientificity of statistics, provide comprehensive information for patients, and continuously improve the management level of hospitals (71). At the same time, it is necessary to strengthen the publicity to the public, make the information open, inform the patients of the payment method of medical insurance in time, so that the patients can enjoy the autonomy in the payment method, so that the patients can actively cooperate with the doctors and make reasonable choices in the treatment process, and improve the patients' willingness to adopt DRGS (54).

5.1. Theoretical significance

As a product of the era of medical and health system reform, DRG medical insurance payment reform has affected the development of hospital operation management, budget management, internal control, and performance management to a certain extent. DRG has injected new impetus into the high-quality development of various medical institutions. In order to improve the use effect of the DRG payment system, this study conducts research on the content of medical insurance DRG payment, and makes several theoretical contributions to this field. First, this study focused on patients' willingness to adopt the DRG payment system. Although there have been more and more studies on medical insurance DRG in recent years, most of them focus on medical institutions and medical insurance funds, and few studies focus on the perspective of patients. However, the essence of the reform of DRG payment methods is to benefit medical insurance Therefore, it is necessary to conduct an in-depth discussion on the perspective of patients, and this study broadens the scope of research in this field (72). Secondly, this study explores the impact of risk perception and trust perception on patients' adoption of DRG system, which enriches the application of risk perception theory and trust perception theory in the medical field. The research results show that improving patients' trust perception and reducing patients' risk perception are conducive to improving patients' willingness to adopt DRG. In order to improve or reduce these two internal perception states of patients, the key lies in the disclosure of medical insurance information. Finally, this study broadens the application of information disclosure theory in the healthcare field. Information disclosure, as an important tool to reduce information asymmetry, can be effective in reducing users' risk perceptions. In the process of adopting new health care payments by patient groups, information disclosure should be used to allow patients to clearly understand information related to their own interests, it will achieve the effect of improving patients' sense of trust and reducing their sense of risk.

5.2. Management significance

This study provides some practical implications for various medical institutions in managing medical insurance information

disclosure. First of all, all medical institutions should pay attention to the disclosure of medical insurance information and increase their disclosure (33). The disclosure of medical insurance information by medical institutions is an important way for the public to obtain information. It can enable the public to understand medical insurance policies, understand medical insurance benefits more conveniently, and improve patients' medical experience. Through empirical analysis, this study finds that the disclosure of medical insurance information can enhance patients' trust perception, reduce their risk perception and thus increase their willingness to adopt DRG medical insurance payment methods. DRG is a new medical insurance payment method. In order to improve patients' acceptance of DRG, it is recommended that medical institutions increase the disclosure of medical insurance information, especially the disclosure of information related to patients' interests, and enhance patients' trust in DRG payment methods. In addition, medical institutions should increase the disclosure rate of medical insurance information. At present, the information disclosure of various medical institutions has the characteristics of selective content. Most of them choose to disclose medical insurance information involving a wide range of people, resulting in incomplete disclosure of information, which is not conducive to the public has a comprehensive understanding of medical insurance policies and services, especially for a new payment system DRG, complete information disclosure is even more important, which can help reduce patients' risk perception (73). At the same time, this study also highlights the influence of patients' internal state on the willingness to adopt DRG payment (74). All medical institutions should pay attention to patients' perception, improve patients' sense of trust, and reduce their perception of risk (75).

5.3. Limitations and prospects

This study has several limitations. First of all, the data in this study are limited to patients in individual medical institutions. Such conclusions may not be accurate enough and have certain limitations. In future research work, the scope of data collection can be effectively expanded to achieve effective testing of model research results. Secondly, this study only explored patients' willingness to adopt DRG payment from the perspective of medical insurance information disclosure, and patients' willingness to adopt a new medical insurance payment method is often affected by many aspects, and it can be explored from more dimensions in the future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

ZS: conceptualization. QZ: methodology. XW: software and validation. All authors contributed to the article and approved the submitted version.

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Institutional Review Board Statement: The study was conducted in accordance with the College of Political Science and Public Management and approved by the Institutional review board of College of Political Science and Public Management.

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.

Publisher's note

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Correlates of residents' enrolment intention toward inclusive commercial health insurance in China: involvement, perceived benefit, perceived sacrifice, and government participation

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Background: As an application of inclusive finance in health insurance, inclusive commercial health insurance (ICHI) is a new public-private partnership-based health insurance scheme and has been vigorously promoted by the Chinese government in recent years to develop China Multi-level Health Insurance System, a system that aims to seek a mix of public and private sources to provide more affordable financial protection to all levels of society in line with their needs. However, the overall enrolment of ICHI scheme is still at a low level, and little is known about what influences residents' enrolment intentions. The aim of this study was to examine the multidimensional factors influencing residents' behavioral intentions and to develop a multivariate conceptual model to explore the psychographic process in the formation of enrolment intention.

Methods: The empirical data used for model validation were obtained from a cross-sectional study conducted in Nanjing, China, a representative pilot city of ICHI scheme in 2022. Exploratory factor analysis, ANOVA, standard multiple regression, and hierarchical multiple regression were mainly employed for hypothesis testing.

Results: The findings revealed that involvement, perceived benefit, and perceived sacrifice are all crucial psychographic process factors in the formation of residents' enrolment intentions. Government participation positively moderates the influence path of "perceived benefit—enrolment intention" but negatively moderates the path of "perceived sacrifice—enrolment intention". Moreover, it was discovered that perceived benefit mediates the effect of involvement on enrolment intention, while perceived sacrifice does not.

Conclusions: Improving residents' perceived benefit and involvement degree of the product, as well as reducing their perceived sacrifice, are both key to increasing their enrolment intentions. This study also points out that one of the main dilemmas in the current development of ICHI scheme is the low level of involvement among residents, and that optimizing the product design to make it more relevant to residents' lives is a more beneficial strategy to increase overall involvement.

KEYWORDS

inclusive commercial health insurance, China, enrolment intention, involvement, perceived benefit, perceived sacrifice, government participation

Background

Inclusive Commercial Health Insurance (ICHI) is a new type of public-private partnership-based voluntary health insurance scheme vigorously promoted by the Chinese government in recent years. It is also the application of "Inclusive Finance" in the field of health insurance. Inclusive finance is a core concept of finance that refers to equitable access for all levels of society, at affordable costs, to a wide range of financial services, provided by a variety of sound and sustainable institutions (1–3). The idea of inclusive finance came from the International Year of Microcredit (2005), launched by the United Nations and the World Bank to recognize the critical role inclusive finance plays in expanding access to financial services for low- and middle-income households as well as helping them in resisting risks (1).

ICHI scheme is city-customized, and its inclusiveness is mainly reflected in three aspects: (1) Low premium and community rating. ICHI scheme adopts community rating, and the average premium nationwide is <0.28% of disposable income per capita (2021). This makes ICHI affordable for almost all households, even those in poverty. (2) Low threshold for enrolment. There is no restriction on age or occupation and no strict restriction on pre-existing medical conditions, which makes ICHI accessible to all groups in society, especially to older adult groups and those with pre-existing health problems. (3) High benefit ceiling. As a complementary insurance to basic social health insurance, ICHI focuses on covering high out-of-pocket expenses (especially for serious and catastrophic diseases) after reimbursement by basic social health insurance, with a benefit ceiling of RMB 1 million. This will help most households to withstand the financial shock of catastrophic health expenditure due to serious diseases.

Public-private partnerships are the foundation on which ICHI scheme operates. Specifically, the underwriter of ICHI scheme is usually a co-insurer formed by several large insurance companies under the guidance of the local government, so, in essence, ICHI scheme is a private health insurance. The government makes overall planning or assists in formulating insurance guarantee plans, participates in product design and promotion, and provide supports such as sharing health insurance data. With the joint efforts of the government and insurance companies, as of 31 December 2021, ICHI scheme has been launched in 244 prefecture-level cities, with a cumulative total of about 140 million enrolments (including second-year renewals) and a total premium size of about RMB 14 billion (4).

From the perspective of insurance economics, the operation of such a low-premium insurance requires a large risk pool. However, the overall resident enrolment rate of ICHI scheme is only around 5% nationwide, and the enrolment rate in most cities has remained relatively low, which is not sufficient to form a sustainable premium pool to share the risk (4–6). In other words, higher resident enrolment will be key to the financially sustainable development of ICHI scheme. From the perspective of developing the broader health system, a higher enrolment rate will make ICHI scheme a core component of China Multi-level Health Insurance System, a system that seeks a mix of public and private sources to provides more supplementary insurance schemes on top of basic social health insurance, as ICHI scheme is expected to fill the gap between the "basic" protection of social health insurance and the "high-premium" protection of private health insurance. Furthermore, from the perspective of international impact, the sustainability of the ICHI scheme will provide a practical model for other social health insurance-led countries to link social insurance and private insurance, with the aim of alleviating the growing financial pressure of social health insurance as a single payer. Based on the above, it is of particular importance to further increase resident enrolment at this stage.

Since ICHI is a new type of insurance scheme originated in China, there is an absence of research specific to ICHI scheme in international context yet. Chinese scholars' literature on how to increase resident enrolment of ICHI scheme mainly focuses on theoretical research and macro data analysis. Most scholars focused on its special "dual supplier" and studied from the perspective of the government and insurance companies, mainly by analyzing the government's macro development data for products in representative cities (7, 8) and the operational effectiveness of inclusive public-private partnership model (9–11), as well as discussing the design logic of existing products and the operating model of insurance companies (5, 6, 12). Despite the optimization of public-private partnership model and insurers' operating models, as well as greater government advocacy to encourage residents into the ICHI system, many residents still choose to drop or refuse to enroll in ICHI scheme. This environment surrounding the ICHI system suggests the need to explore a new question. In the case of voluntary health insurance, the focus is not only on the sound operation of the supply side, but we need to be aware that residents' subjective behavioral intention to purchase is the direct internal motivation for their choice to enroll. Therefore, understanding the motivational factors and barriers that can explain residents' behavioral intentions toward ICHI from a demand-side perspective is essential to finding ways to increase the enrolment. In this context, this study aims to contribute to knowledge on this topic by identifying the multidimensional factors that influence residents' behavioral intentions toward ICHI scheme, exploring the multivariate psychographic process in the formation of their enrolment intention, and developing a conceptual model to describe the interrelationships between the key psychographic factors. Finally, feasible suggestions for health policymakers and promoters to increase ICHI enrolment among residents would be put forward according to the research results.

Research factors and theoretical framework

Given that ICHI has stronger private health insurance attributes from a demand-side perspective, the theoretical part of this study was based on broader research on private health insurance to explore the factors influencing residents' enrolment intention. Particularly, the following variables are examined and explained in the following paragraphs: enrolment intention, perceived value variables (i.e., perceived benefit and perceived sacrifice), involvement and government participation.

Abbreviations: ICHI, Inclusive Commercial Health Insurance.

Enrolment intention is the dependent variable in this study which refers to the subjective tendency of residents to invest in ICHI scheme, and it also directly reflects the possibility of making the enrolment decision (13, 14). Previous literature has suggested that people would have a greater intention to enroll in health insurance if they perceive the potential benefits outweigh the costs (15). This trade-off of benefit and sacrifice often relies on Perceived Value Theory in marketing. According to Zeithaml (16), perceived value is defined as the overall evaluation of the product by consumers after comprehensively considering the perceived benefits and the sacrifices, and it can influence consumers' purchase behaviors. In the field of studies of health insurance, perceived value as a pre-influencing factor of behavioral intention has been used in several studies and a causal relationship was found between them (15, 17, 18).

In practical empirical studies, the perceived value variable can be divided into perceived benefit and perceived sacrifice in order to better measure it (16, 19). Many studies based on the above classification of perceived value has suggested that perceived benefit has a positive influence on behavioral intention to invest, while perceived sacrifice has a negative influence (20–22). Thus, this study proposed the following hypotheses:

H1a: Perceived benefit positively influences residents' enrolment intention toward ICHI scheme.
H1b: Perceived sacrifice negatively influences residents' enrolment intention toward ICHI scheme.

However, the use of perceived value as an independent variable to measure behavioral intention assumed perfect and equal knowledge amongst individuals who can make comprehensive consideration and trade-off between benefits and costs. In fact, most consumers are often in a state of information asymmetry and do not have a strong subjective intention to collect and process more information regarding products that are not of interest to them or that they feel less relevant to. Therefore, it is difficult for them to make such a comprehensive consideration. To solve this problem, an antecedent factor of perceived value is needed to describe consumers' perceived relevance to the product and to explain the process of information collection and processing. Based on literature reviews, Involvement was considered a suitable antecedent factor which is defined as a motivational variable reflecting the degree of a person's perceived relevance of the object to the individual based on his inherent needs, values, and interests (23). It has been proposed by precious literature that, when making decisions, individuals with deeper involvement tend to search for more information and more proactively (24), process relevant information more systematically (25), and will have a more comprehensive consideration on the strengths and weaknesses of possible alternatives (26). Therefore, the degree of a consumer's involvement will have an impact on information processing and consideration of benefits and sacrifices (26–28). Moreover, several studies have demonstrated that involvement has a positive impact on consumers' perception of benefits, while their perception of sacrifice decreases with increasing involvement and duration (29, 30). Therefore, the following hypotheses were proposed:

H2a: Involvement positively influences residents' perceived benefit of enrolling in ICHI.
H2b: Involvement negatively influences residents' perceived sacrifice of enrolling in ICHI.

In addition to the impact of involvement on perceived value, involvement was often seen as an important psychographic construct due to its potential influence on consumer's behavior with respect to decision making and purchase intention (31, 32). It has been suggested in many empirical studies that involvement has a positive influence on consumers' behavioral intention to purchase (33–35). Therefore, we proposed the following hypothesis:

H3: Involvement positively influences residents' enrolment intention toward ICHI scheme.

Furthermore, according to Liang and Lai (36), it was believed that consumers will pass "Problem recognition—Information collection—Evaluation of alternatives—Purchase process evaluation—Post-purchase services evaluation" five stages, and finally form behavioral intentions and make a purchase decision. In this study, involvement refers to residents' perception of the relevance to ICHI based on their inherent needs, values, and interests, including the process of problem recognition and information collection. In contrast, perceived value refers to a comprehensive evaluation of ICHI scheme after weighing the benefits and sacrifices. This evaluation includes alternatives before purchase, the purchase process, and post-purchase services, the last of which is especially vital for insurance products. Therefore, we deduced there was an influence pathway of "involvement—perceived value—enrolment intention" between the three variables, and similarly, many studies have shown that perceived value mediates the effect of involvement on behavioral intention (37–39). Therefore, the following hypotheses were proposed:

H4a: Perceived benefit mediates the effect of involvement on enrolment intention toward ICHI scheme.
H4b: Perceived sacrifice mediates the effect of involvement on enrolment intention toward ICHI scheme.

In addition, according to previous research conducted for this study, it has been clarified that ICHI scheme is subject to a certain degree of government intervention. Many studies have shown the role of government as promoter and regulator of ICHI scheme in enhancing residents' perception of benefits, reducing their perceived risk, and thus increasing their enrolment intention (4, 9, 11). Thus, this study proposed the following hypotheses:

H5a: Government participation moderates the relationship between perceived benefit and enrolment intention toward ICHI scheme.
H5b: Government participation moderates the relationship between perceived sacrifice and enrolment intention toward ICHI scheme.

Figure 1 shows the theoretical model proposed in this study.

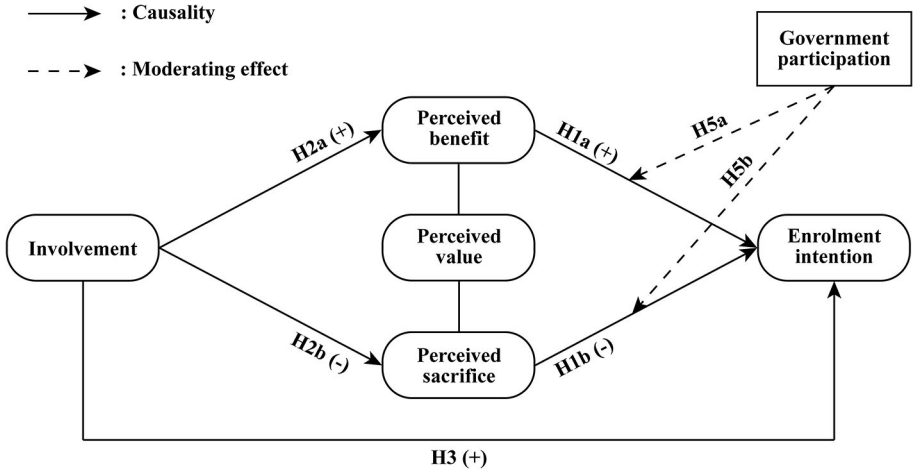

FIGURE 1
Hypothesized model to be tested.

Methods

Measure

An offline questionnaire was developed to measure the variables and test the hypotheses. The questionnaire consists of two parts involving demographic questions and the measurement of model construct variables. All survey items in the latter part utilized a 5-point Likert scale ranging from "agree strongly" to "disagree strongly". They were developed based on existing literature, including five constructs (see Table 1):

(a) Involvement. To determine the measurement structure of involvement, this study was mainly based on Zaichkowsky's (23) Personal Involvement Inventory and proposed to subdivided involvement into three dimensions: product involvement, advertising involvement and enrolment-decision involvement. Specifically, product, advertising and enrolment-decision involvement respectively refer to the relevance degree to which consumers perceive the ICHI scheme itself (23), the advertising information (40) of ICHI, and the decision to enroll (41) in ICHI scheme to themselves. The items measuring each dimension were developed from the existing literature (23, 42, 43), with a total of eight items.

(b) perceived benefit and (c) perceived sacrifice. The measurement structure of perceived value has been investigated in many ways, for example, Richins and Dawson's (44) Material Values Scale (MVS) and Sweeney and Soutar's (45) Perceived Value (PERVAL) scale. In this study, we first divided perceived value into perceived benefit and perceived sacrifice. For a more systematic measurement of each construct, perceived benefit was subdivided into five dimensions: product value, service value (46), functional value, emotional value, and price value (45, 47), as well as perceived sacrifice into two dimensions: purchase cost and perceived risk (46). The items measuring each dimension were developed from the existing literature: perceived benefit (measured by ten items) (16, 45–47), perceived sacrifice (measured by six items) (19, 46).

(d) government participation (measured by three items, developed from this study); and (e) enrolment intention (measured by three items) (14, 48). The specific Likert scale items of the questionnaire are shown in Supplementary material.

Data collection

The process of data collection was shown in Figure 2. We conducted a cross-sectional survey using Nanjing as the sample area, because Nanjing is the second earliest city in China to start piloting ICHI scheme. Since the first-generation product was launched in 2018, after nearly 4 years of practice, Nanjing ICHI scheme has had a relatively higher penetration rate than other cities in China (6). As a result, the data obtained from Nanjing was believed to be more representative and meaningful for research purposes. We conducted a pilot study prior to the formal research, collecting 51 valid questionnaires with a Cronbach's alpha coefficient of 0.917 that passed the reliability test. Ten researchers received comprehensive training in research-related matters before the formal research began. To make the sample more representative of the population, a stratified random sampling method was used to divide the 12 districts of Nanjing into three tiers based on the level of economic development (with reference to the GDP of each district in 2020). One district from each tier was extracted for an offline random interview-style question-and-answer survey, and the number of questionnaires was allocated according to the number of residential population in the corresponding district. As the ICHI scheme is voluntarily purchased and based on a supplement to the basic social health insurance, all respondents are selected over 18 years of age and have basic social health insurance. The total number of distributed questionnaires was 400. Excluding incomplete surveys, surveys that mark the same box throughout the

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TABLE 1 Factor loadings, mean, and standard deviation (SD) of each survey item's mean.

Constructs	Measurement dimensions	Codes	Factor loadings				Mean	SD
			F1	F2	F3	F4		
Involvement α = 0.937 KMO = 0.903*** Variance explained = 67.80 (%)	Advertising involvement	A1	0.874				2.99	1.046
		A2	0.910				3.00	1.021
		A3	0.886				3.02	1.043
	Product involvement	A4		0.925			2.98	1.027
		A5		0.881			3.05	1.002
		A6		0.835			2.83	1.059
	Enrolment-decision involvement	A7			0.713		3.05	0.913
		A8			0.608		3.19	0.876
Perceived benefit α = 0.796 KMO = 0.804*** Variance explained = 70.44 (%)	Product value	B1	0.547				3.36	0.815
		B2	0.642				3.28	0.987
	Functional value*	B3		0.838			3.36	0.833
		B4		0.847			3.41	0.860
		B5		0.875			3.28	0.907
		B6		0.859			3.16	0.888
	Service value	B7			0.602		3.44	0.740
		B8			0.831		3.75	2.387
	Price value	B9				0.881	3.86	0.782
		B10				0.859	3.79	0.896
Perceived sacrifice α = 0.924 KMO = 0.884*** Variance explained = 73.11 (%)	Perceived cost*	C1	0.680				3.16	0.890
		C2	0.932				3.40	1.022
		C3	0.942				3.40	1.016
		C4	0.941				3.33	1.005
		C5	0.907				3.31	1.000
		C6	0.677				3.42	0.988
Government participation α = 0.951 KMO = 0.759*** Variance explained = 91.07 (%)	Government actions	D1	0.936				4.07	0.805
		D2	0.964				4.13	0.784
		D3	0.962				4.13	0.794
Enrolment intention α = 0.949 KMO = 0.735*** Variance explained = 90.78 (%)	Enrolment-related actions	E1	0.968				2.93	1.138
		E2	0.969				2.82	1.098
		E3	0.921				2.99	1.072

α, Cronbach's alpha; KMO, Kaiser-Meyer-Olkin.
Measurement dimension* indicates that this theoretical dimension was adjusted based on EFA.
***$p < 0.001$.

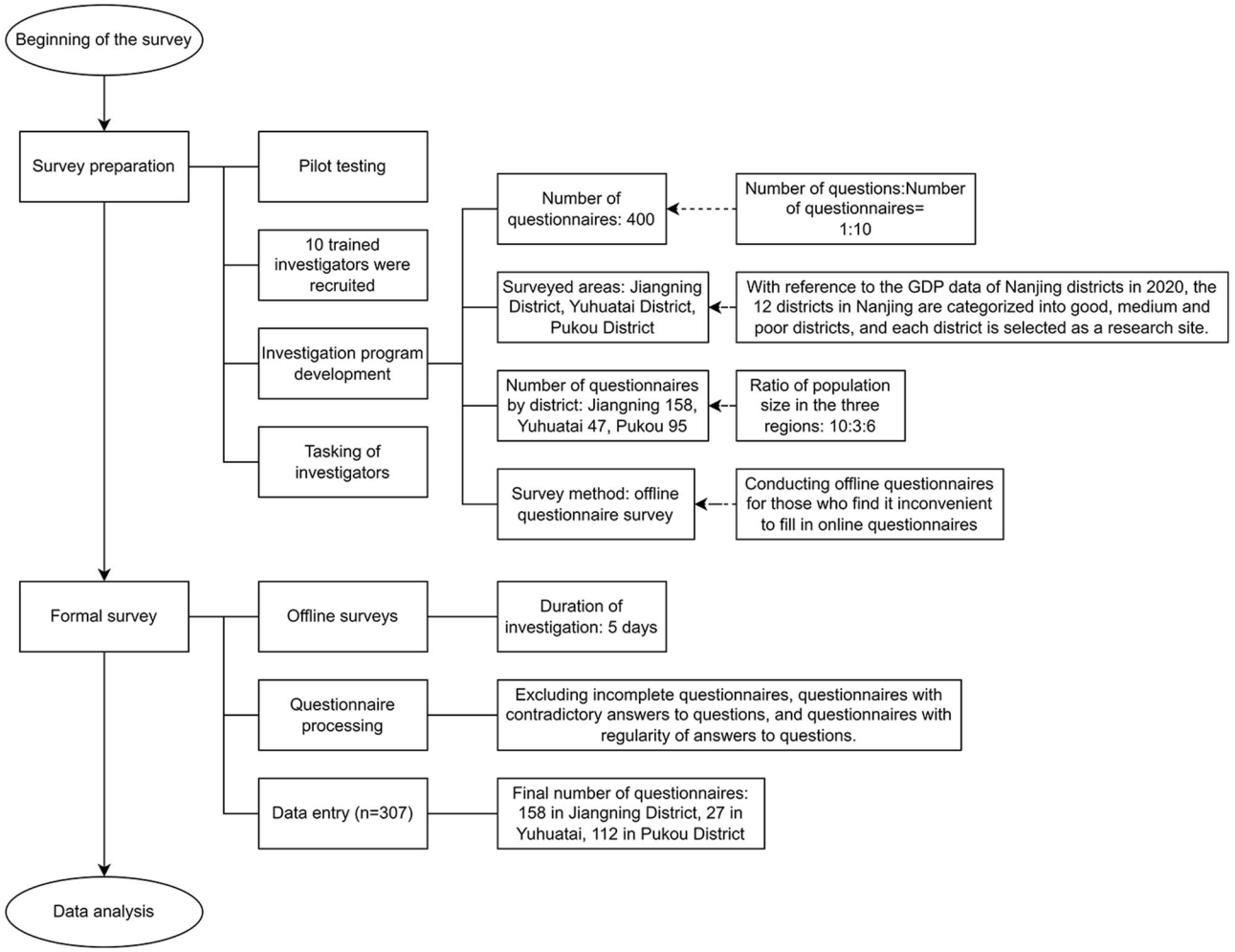

FIGURE 2
The process of data collection.

entire questionnaire, surveys with conflicting answers, surveys that have a residence outside of Jiangning, Yuhuatai, and Pukou districts in Nanjing, and surveys that lack basic medical insurance coverage in Nanjing, the total number of valid surveys collected was 307, with a validity rate of 76.75%, meeting the analysis requirements. The studies involving human participants were reviewed and approved by Ethics Committee of China Pharmaceutical University. The patients/participants provided their written informed consent to participate in this study.

Data analysis

Prior to hypotheses testing, Exploratory Factor Analysis (EFA) using principal component analysis (PCA) with Varimax-Rotation (49) was conducted on the survey items within each construct using SPSS Version 23. This ensured the latent structure of the observed constructs and variables (50), which was necessary as these items were adopted from existing literature but were applied in the context of ICHI. Table 1 shows the factor analysis results of each research construct (the factor loadings, the mean and standard deviation (SD) of the mean for each item that was retained). The factor loadings of retained items ranged from 0.547 to 0.969. The Cronbach's Alpha of each model construct ranged from 0.796 to 0.951. The Kaiser-Meyer-Olkin (KMO) measure of adequacy for each research variable ranged from 0.735 to 0.903. The Bartlett's test of sphericity was significant for all variables. The variance explained ranged from 67.80 to 91.07%. The eigenvalues of all retained factors were all above 1. According to the results of EFA, we combined functional and emotional value into one dimension, namely functional value, and incorporated purchase cost and perceived risk into perceived cost dimension. These results showed that the items were adequate to explain the latent variables and had a good construct validity (51). Additionally, we tested for the presence of common method bias (CMB) through Harman's single factor test (52). SPSS 26 was used for conducting Exploratory Factor Analysis, where all items were included. The examination revealed that all considered measures explained 35.80% of the variance, which is significantly lower than the recommended threshold of 50% (52). Thus, CMB was not present in our study.

Subsequently, descriptive statistics, one-way ANOVA, standard multiple regression, and hierarchical multiple regression were applied for analysis and hypotheses testing.

Results

Respondents' demographics and ANOVA

The demographics of respondents in this study are addressed in Table 2. As can be seen from the table, the sample has a gender ratio close to the true level and could be a good representation of people with a middle-level of spending power, some health problems, and some knowledge of health insurance, who are exactly the target outreach population of ICHI scheme and the main component of the risk pool. Therefore, the sample was relatively well suited to the needs of this study.

A one-way ANOVA was conducted to examine which of the demographic variables had an impact on enrolment intention. Significant associations were found between enrolment intention and demographic variables of age, education level, whether having private health insurance, and whether suffering from chronic, rare, or serious diseases (see Table 2). Among these demographic variables, the impact of whether having private health insurance ($t = 27.328$, $p < 0.001$) was the most significant. It is also noteworthy that residents with existing private health insurance (Mean = 3.227) have a higher intention to enroll than those without other private health insurance (Mean = 2.665). Contrary to our expectations, disposable personal income was not associated with enrolment intention.

Regression analysis

Test of multicollinearity

The multicollinearity test is important for multivariate analysis, which requires that the two independent variables should not perform the same work in a single regression model. The multicollinearity test method suggested by Hair et al. (53) utilized variance inflation factor (VIF) and tolerance analysis. Generally, when the tolerance is <0.20 or VIF is >5 (VIF × Tolerance = 1), it indicates that there is a multicollinearity problem (53). As shown in the Collinearity Statistics columns in Table 3, there is no multicollinearity among the independent variables of each construct in this study.

Regression analysis and hypotheses testing

Table 3 presents the results of standard multiple regression tests on H1-H3. In model 1, the results demonstrated that all three dimensions of involvement: advertising involvement ($\beta = 0.150$, $p = 0.003$), product involvement ($\beta = 0.288$, $p < 0.001$), and enrolment-decision involvement ($\beta = 0.071$, $p = 0.012$) had a statistically significant positive impact on the perceived benefit (see Table 3). The largest Beta value in this model was 0.417, which is for product involvement, followed by advertising involvement (Beta = 0.225). This indicates that the product involvement variable makes the greatest unique contribution to explaining perceived benefit when the variance explained by other variables in the model was controlled. Altogether, 44.6% of the enrolment intention among residents was explained by knowing the scores for the three dimensions of Involvement ($F = 83.173$, $p < 0.001$, adjusted $R^2 = 0.446$). Based on the above results, H2a was accepted.

In model 2, the regression coefficients of advertising involvement ($\beta = -0.158$, $p = 0.055$) and product involvement ($\beta = -0.168$, $p = 0.070$) in the three measurement dimensions of involvement did not pass the T-test with a significance level of 0.05. In addition, the regression model did not pass the F-test with a significance level of 0.05, and the adjusted R^2 is only 0.076, indicating a poor model fitness. Based on the above results, it was reasonable to conclude that H2b was rejected.

In model 3, the results showed that all the four dimensions of perceived benefit: product value ($\beta = 0.086$, $p = 0.008$), functional value ($\beta = 0.499$, $p < 0.001$), service value ($\beta = 0.107$, $p = 0.004$), and price value ($\beta = 0.326$, $p < 0.001$) had a positive impact on enrolment intention. Among these dimension variables, the impact of functional value (Beta = 0.373) and price value (Beta = 0.248) was relatively stronger. Altogether, the four dimensions of perceived benefit can explain 39.9% of the change in enrolment intention ($F = 51.884$, $p < 0.001$, adjusted $R^2 = 0.399$). Therefore, H1a was accepted.

Model 4 indicated that perceived sacrifice ($\beta = -0.207$, $p < 0.001$) had a negative impact on the enrolment intention ($F = 14.889$, $p < 0.001$, adjusted $R^2 = 0.216$), and results in model 5 showed that all the three dimensions of involvement: advertising involvement ($\beta = 0.039$, $p = 0.003$), product involvement ($\beta = 0.686$, $p < 0.001$), and enrolment-decision involvement ($\beta = 0.133$, $p = 0.045$) had a significant positive impact on enrolment intention. In addition, the F-test results and adjusted R^2 in model 5 ($F = 110.039$, $p < 0.001$, adjusted $R^2 = 0.517$) indicated a good model fitness. Based on the above results, H1b and H3 were accepted. Furthermore, it was discovered that product involvement showed a stronger influence capability in both model 1 (Beta = 0.417) and model 5 (Beta = 0.623).

Mediation effect analysis

As per Baron and Kenny's (54) approach, mediating effect is tested in the following steps (X: independent variable; Y: dependent variable; M: mediator variable): (1) regress M on X, and look for a significant coefficient associated with X; (2) regress Y on X, and look for a significant coefficient associated with X; (3) regress Y on X and M, and look for a significant coefficient associated with M, then the mediating effect was demonstrated when the effect of X on Y was less in the third regression equation than in the second.

For H4b, it has been found that involvement (independent variable) does not affect perceived sacrifice (mediator variable) in the upper subsection. As a result, H4b was rejected. Then, for the test of H4a, model 6–7 were used for the steps 1–2 respectively, and they all had good fitness and significant regression coefficients [model 6: β for X (involvement) = 0.528, $p < 0.001$, adjusted $R^2 = 0.444$; model 7: β for X (involvement) = 0.883, $p < 0.001$, adjusted $R^2 = 0.489$] (see Table 4). Then model 8 shows the regression results in the test of step (3). The mediator variable perceived

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TABLE 2 Sample demographics and the analysis of enrolment intention by demographic variables using one-way ANOVA.

Demographics	Proportion (%)	One-way ANOVA			
		Mean	SD	*t*-value	Sig.
Gender				2.013	0.157
Male	45.60	2.821	0.985		
Female	54.40	2.992	1.100		
Age				2.289	0.046
18–25	19.87	2.962	0.817		
26–35	34.53	3.025	1.111		
36–45	13.68	3.167	1.155		
46–55	12.70	2.821	0.964		
56–60	6.51	2.567	0.845		
>60	12.70	2.914	1.051		
Education level				4.710	0.001
Junior high school and below	18.57	2.626	0.928		
High school or secondary school	14.66	2.504	0.958		
College	16.29	2.973	0.992		
Bachelor's degree	42.35	3.090	1.095		
Master's degree and above	8.14	3.280	1.057		
Whether having private health insurance				27.328	0.000
Yes	40.72	3.277	0.968		
No	59.28	2.665	1.036		
Disposable personal income (RMB)				0.725	0.605
<20,000	22.48	2.783	0.996		
20,001–40,000	12.38	2.912	0.909		
40,001–60,000	14.98	2.797	1.039		
60,001–80,000	10.75	2.879	1.133		
80,001–100,000	13.03	3.000	1.035		
>100,000	26.38	3.066	1.143		
Self-assessment of physical health				2.109	0.080
Very good	20.52	2.735	0.958		
Fairly good	53.75	3.004	1.063		
Medium level	22.48	2.971	1.054		
Relatively poor or very bad	3.26	2.167	1.114		
Whether suffering from chronic disease, rare disease, and serious disease				5.482	0.020
Yes	14.66	2.578	1.142		
No	85.34	2.972	1.026		
Average annual personal medical expenses (RMB)				0.300	0.878
<5,000	80.78	2.891	1.070		
5,001–10,000	11.07	2.971	0.866		
10,001–20,000	4.23	2.949	1.008		
20,001–50,000	2.28	3.286	1.177		
>50,000	1.63	3.067	1.479		

TABLE 3 Summary of coefficients for the standard multiple regression of the hypotheses testing on H1–H3.

	Models	Unstandardized coefficients		Standardized coefficients	*T*-test	Collinearity statistics
	Independent variables	B	Std. error	Beta (β)	Sig.	VIF
1	Advertising involvement	0.150	0.050	0.225	0.003	3.072
	Product involvement	0.288	0.056	0.417	<0.001	3.647
	Enrolment-decision involvement	0.071	0.044	0.087	0.012	1.664
2	Advertising involvement	−0.158	0.082	−0.186	0.055	3.072
	Product involvement	−0.168	0.092	−0.191	0.070	3.647
	Enrolment-decision involvement	0.280	0.073	0.073	<0.001	1.664
3	Product value	0.086	0.077	0.061	0.008	1.551
	Functional value	0.499	0.075	0.373	<0.001	1.610
	Service value	0.107	0.037	0.136	0.004	1.130
	Price value	0.326	0.072	0.248	<0.001	1.513
4	Perceived sacrifice	−0.270	0.070	−0.216	<0.001	1.000
5	Advertising involvement	0.039	0.074	0.036	0.003	3.072
	Product involvement	0.686	0.084	0.623	<0.001	3.647
	Enrolment-decision involvement	0.133	0.066	0.102	0.045	1.664

The dependent variable: perceived benefit (model 1); perceived sacrifice (model 2); enrolment intention (model 3–5). Adjusted $R^2 = 0.446$ for model 1; Adjusted $R^2 = 0.076$ for model 2; Adjusted $R^2 = 0.399$ for model 3; Adjusted $R^2 = 0.216$ for model 4; Adjusted $R^2 = 0.517$ for model 5.

TABLE 4 Summary of coefficients in the standard multiple regression for mediating effect analysis.

	Models	Dependent variable	Model coefficients			Model summary
	Independent variables		β	Std. Error	Sig.	Adjusted R^2
6	Involvement	Perceived benefit	0.528	0.034	0.000	0.444***
7	Involvement	Enrolment intention	0.883	0.052	0.000	0.489***
8	Involvement	Enrolment intention	0.652	0.066	0.000	0.529***
	Perceived benefit		0.437	0.084	0.000	

***$p < 0.001$.

benefit had a significant effect on enrolment intention ($\beta = 0.437$, $p < 0.001$), and the effect of involvement on enrolment intention was less than the effect in the regression model 7, as evidenced by a decrease in the regression coefficient ($\beta_{\text{model 8}} = 0.652 < \beta_{\text{model 7}} = 0.883$). Thus, all the assumptions of Baron and Kenny's method were satisfied, and H4a was accepted.

Moderating effect analysis

According to the model test method proposed by Wen-Zhonglin and Hou (55) involving both mediator variables and moderator variables, this study adopts the sequential test method to verify the moderating effect of the moderated mediation model involved in this study, which is divided into four steps (X: independent variable; Y: dependent variable; M: mediator variable; W: moderator variable): (1) regress Y on X and W, and look for a significant coefficient associated with X; (2) regress M on X and W, and look for a significant coefficient associated with X; (3) regress Y on X, W, and M; and look for a significant coefficient associated with M; (4) regress Y on X, W, M, and W×M; A significant coefficients associated with W×M suggests that the relationship between M and Y is moderated by W.

Table 5 shows the results of the regression analysis. Model 9–11 were used for the tests of steps 1–3 respectively, and they all had good fitness and significant regression coefficients [model 9: β for X (involvement) = 0.832, $p < 0.001$, adjusted $R^2 = 0.521$; model 10: β for X (involvement) = 0.492, $p < 0.001$, adjusted $R^2 = 0.484$; model 11: β for M (perceived benefit) = 0.356, $p < 0.001$, adjusted $R^2 = 0.545$]. After including an interaction term for perceived benefit and government participation, model 10 still showed significant regression results and good model fitness [β for W×M (Government participation × Perceived benefit) = 0.209, $p = 0.02 < 0.05$, adjusted $R^2 = 0.576$]. Thus, all the assumptions of Wen-Zhonglin and Hou's (55) method were satisfied, implying that government participation positively moderates the effect of perceived benefit on enrolment intention. Therefore, H5a was accepted.

Having determined that perceived sacrifice is not a mediator variable between involvement and enrolment intention, hierarchical regression analysis was conducted to examine

TABLE 5 Summary of coefficients in the standard multiple regression for moderating effect analysis.

	Models	Dependent variables	Model coefficients			Model summary
	Independent variables		β	Std. error	Sig.	Adjusted R^2
9	Involvement	Enrolment intention	0.832	0.051	0.000	0.521***
	Government participation		0.260	0.056	0.000	
10	Involvement	Perceived benefit	0.492	0.033	0.000	0.484***
	Government participation		0.181	0.037	0.000	
11	Involvement	Enrolment intention	0.657	0.065	0.000	0.545***
	Government participation		0.195	0.057	0.001	
	Perceived benefit		0.356	0.086	0.000	
12	Involvement	Enrolment intention	0.646	0.065	0.000	0.576***
	Government participation		−0.507	0.305	0.097	
	Perceived benefit		−0.517	0.382	0.177	
	Government participation × Perceived benefit		0.209	0.089	0.020	
13	Perceived sacrifice	Enrolment intention	−0.278	0.066	0.000	0.552***
	Government participation		0.462	0.073	0.000	
14	Perceived sacrifice	Enrolment intention	−0.272	0.060	0.027	0.557***
	Government participation		0.460	0.070	0.002	
	Perceived sacrifice × Government participation		−0.154	0.005	0.005	

***$p < 0.001$.

the moderating effect of government participation on perceived sacrifice and enrolment intention. Model 13–14 in Table 5 illustrates the results of hierarchical regression analysis. After adding the moderator variable Government participation to the regression model, model 13 showed that government participation had a positive influence on enrolment intention ($\beta = 0.462$, $p < 0.001$). When including an interaction term for perceived sacrifice and government participation (model 14), regression coefficient of perceived sacrifice × government participation was significant ($\beta = -0.154$, $p = 0.005$). The results indicated that government participation had a negative moderating effect of perceived sacrifice on enrolment intention. H5b was thus accepted.

Modification of the theoretical model

To sum up, results of the analysis above showed that the hypotheses proposed in this study are valid except for H2b and H4b. Figure 3 shows the revised conceptual model.

Discussion

The findings from this study provide a more holistic picture of the multidimensional factors that influence residents' enrolment intention as well as their influencing mechanisms, from a demand-side perspective. In exploring the influence of control variables, we found that there are demographic variables (e.g. age, education level, health status, and existing level of insurance coverage) that influenced residents' enrolment intention, and the impact of existing level of insurance coverage was the most significant. Among the demographic variables studied in this study, it is noteworthy that income level has no effect on enrolment intention. This could be explained by the low premiums of ICHI scheme, which account for a relatively small percentage of residents' total income. To conclude, in the future promotion to more cities, designers of ICHI scheme should pay increased attention to the influence of the differing individual characteristics of residents in different cities on their intentions to enroll. Moreover, our findings also provided additional evidence and pilot directions for many domestic scholars who advocate the city-differentiated customized insurance schemes (6, 12).

Then, based on the revised conceptual model of the psychographic factors influencing enrolment intention, we found the following: First, we discovered a statistically significant positive impact of involvement on both perceived benefit and enrolment intention. Reflecting on the difference in the influence capability of three dimensions of involvement, it is noted that the impact of product involvement is the strongest. This indicated that more attention should be paid to the product design to make it more related to residents' lives in future development, because this factor is not only an instrumental pre-factor for the formation of residents' value perception, but also a significant driving factor for increased enrolment intention. These findings strengthened the conclusions of existing studies (30, 33, 34) and further complemented the differing influence capabilities of the different dimensions of involvement as well.

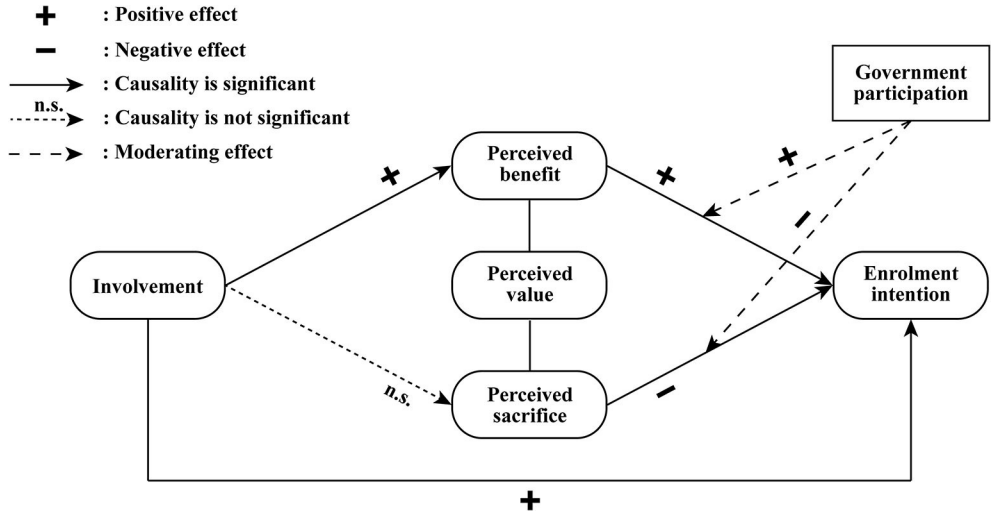

FIGURE 3
Conceptual model of the factors influencing residents' enrolment intention.

Second, our research revealed that involvement does not affect residents' perceived sacrifice, and the mediating effect of perceived sacrifice between involvement and enrolment intention is therefore not significant. This might seem to be in conflict with Venkatraman's research (29). On the other hand, residents' perceived benefit was found to mediate the effect of involvement on enrolment intention. These findings suggested that the reason why residents' enrolment intention increases with the deepening of involvement is that they are more aware of benefits brought by ICHI scheme, rather than their decreased concern over potential sacrifices. One possible explanation is that the overall involvement among residents is currently low. According to the study of Maheswaran and Meyers-Levy (26), individuals in the low involvement condition often draw and apply the inference that they agree more with issues associated with positive rather than negative information, while under high involvement individuals would presumably assign more weight to the negatively framed rather than the positively framed information and be more persuaded by it. This explanation was also consistent with the descriptive statistical analysis of each model construct variable that the average score of involvement was the lowest (see Table 1). Thus, at the current stage, policymakers and product providers should seek to improve the overall involvement of residents, and to achieve this, increasing product involvement by optimizing product design to make it more relevant to residents' lives is considered the most beneficial approach based on the influence capability analysis above.

Third, our results indicated that perceived benefit positively affects residents' enrolment intention while perceived sacrifice negatively affects their enrolment intention, which was in line with the basic connotation of the perceived value theory. In addition, empirical analysis based on further subdivisions of different research dimensions showed that functional value and price value have a more significant impact on enrolment intention. In contrast, the impact of service value and product value is relatively weak. For one thing, product designers can further improve residents' perceived benefit by optimizing existing functional value and price value, as well as expanding additional functional value such as value-added services. For another, product promoters can employ better publicity strategies to reduce residents' enrolment concerns.

Lastly, we found that government participation positively moderates the effect of perceived benefit on enrolment intention. It is conceivable that under the national conditions of China, residents have a trust relationship with the government. This means that involving the government can strengthen residents' perception of the benefits of ICHI scheme, thereby increasing their intention to enroll. However, contrary to our expectation, government participation negatively moderates the effect of perceived sacrifice on enrolment intention. Considering that there have been few quantitative studies on government participation in ICHI scheme, additional research is required to determine the causes of this negative moderating effect. Our future study will refine the measurement dimensions of the government participation variable and take into account factors such as different intervention channels and publicity methods to examine the moderating effect of government participation in greater depth. Last but not least, since government participation does have a significant moderating effect, it is recommended for policymakers to clarify the functional positioning of each participating government department.

On the one hand, this paper further complemented the differing capabilities of the different dimensions of involvement and perceived benefit to influence enrolment intentions, expanding the research boundaries of involvement theory and perceived value theory. On the other hand, research targeting the enhanced sustainability of health insurance programs will provide a practical model for other social health insurance-led countries to link social insurance and private insurance, with the aim of alleviating the growing financial pressure of social health insurance as a single payer. However, the current study is not without limitations. First, this study was limited in scope by several factors, including the epidemic situation, and we only selected one of the most representative cities, Nanjing, to serve as the survey sample area

in this case. Consequently, the research conclusions may have certain regional characteristics instead of being universal. Second, in the absence of well-established scales for measuring government participation variables, the questionnaire development in this section lacks a solid theoretical and practical basis. This may lead to empirical data that may not accurately reflect government participation actions. Lastly, the involvement theory and the perceived value theory are primarily used in the construction of the conceptual model. This may result in that not all influencing factors and intermediate variables are included, such as residents' attitudes toward the product. Future studies could incorporate the attitude variables from the Theory of Planned Behavior, and comprehensively consider the formation mechanism of residents' enrolment intention.

Conclusion

Although ICHI scheme has been rapidly promoted in China under the joint efforts of the government and insurance companies, the overall enrolment rate of residents remains low currently. While existing studies have mostly focused on the supply-side perspective, this study proposed that it is equally important to understand the multidimensional factors that influence residents' behavioral intention from a demand-side perspective. By examining these factors and their interrelationships, this study developed a multivariate conceptual model of the psychographic process by which residents' enrolment intentions are formed. Based on this model, we suggested ways for health policymakers and promoters to increase the enrolment among residents. Through analysis, this study has identified that involvement and the two constructs of perceived value (i.e. perceived benefit and perceived sacrifice) are all crucial psychographic process factors that influence the formation of residents' enrolment intentions, and that government participation is a moderator of this psychographic process. When analyzing the interrelationships between the five constructs in the model, two findings deserve special attention: First, perceived benefit mediates the effect of involvement on enrolment intention, while perceived sacrifice does not. This result indicated that one of the main dilemmas in the current development of ICHI scheme is the low level of involvement among residents. Second, government participation positively moderates the influence path of "perceived benefit—enrolment intention" but negatively moderates the path of "perceived sacrifice—enrolment intention". Further research is required to understand the opposite moderating direction of government participation as a moderator. At the current stage, policymakers and product providers should seek to improve the overall involvement of residents, and to achieve this, increasing product involvement by optimizing product design to make it more relevant to residents' lives is considered the most beneficial approach.

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 authors.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

TS, YW, JX, RS, and RJ contributed to the study design. TS, YW, and XH made contributions to the acquisition, analysis, and interpretation of data. TS prepared the first draft of the manuscript. YW, RS, and RJ made substantial revisions to the manuscript prior to its submission. All authors have approved the submitted version.

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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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1121783/full#supplementary-material

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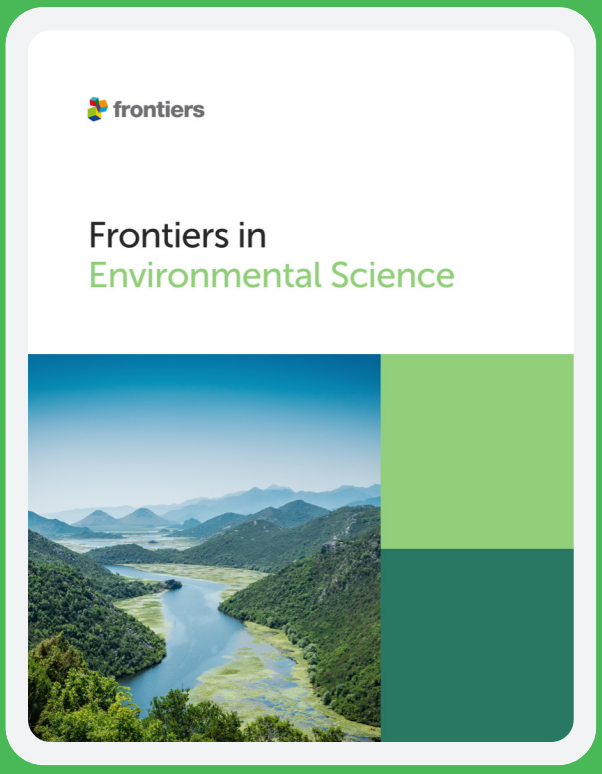

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