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Sustainable economic growth, green deal and macroeconomic recovery – most suitable pathways to recovering from the actual evolutionary hiatus

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Sustainable economic growth, green deal and macroeconomic recovery – most suitable pathways to recovering from the actual evolutionary hiatus

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Sustainable corporate environmental information disclosure: Evidence for green recovery from polluting firms of China

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For a greener society, good corporate environmental information disclosure is crucial. This study empirically examines the influence of media attention and state-owned equity, and their interaction on corporate environmental information disclosure by A-share heavily polluting firms in the Shanghai and Shenzhen stock markets from 2015 to 2019. The results show that state-owned equity can improve the level of corporate environmental information disclosure; however, it mainly affects financial environmental information disclosure. Media attention also improves the level of corporate environmental information disclosure, but only for non-financial environmental information. Moreover, media attention and state-owned equity have a certain substitution effect on environmental information disclosure: a higher state-owned equity ratio weakens the positive effect of media attention on environmental information disclosure. To improve environmental information disclosure, the government must clarify disclosure standards to improve the comparability of environmental information. In addition, media and shareholders can fully leverage their external and internal supervisory roles to promote the environmental responsibilities of firms. Our findings can be useful for further promoting corporate environmental information disclosure and developing relevant policies.

KEYWORDS

media attention, sustainable development, state-owned equity, environmental information, green recovery

1 Introduction

In recent years, constructing a greener and ecologically sustainable civilization has become even more important. Given tightening resource constraints, serious environmental pollution, and ecosystem degradation, we must adhere to the basic policy of conserving resources and protecting the ecological environment, and build an environmental governance system in which the government plays the leading role and firms perform the major role with the participation of the public (Yang et al., 2020). As market entities, firms play an important role in the construction of an ecological civilization, and should actively fulfill their environmental responsibilities and disclose their performance on time.

According to the Evaluation Report on Environmental Responsibility Disclosure of Chinese Listed Companies (2020), only 1,135 of the 4,418 companies listed in the Shanghai and Shenzhen stock markets in 2020 had issued social responsibility or environmental reports. Regarding the disclosure level, the average index of environmental disclosure was 36.4 out of 100; this shows that there is still much room for improvement in corporate environmental disclosure. Regarding the disclosure content, it currently includes financial environmental information, such as emission amount and environmental protection expenditures, as well as non-financial environmental information, such as corporate environmental system and environmental management objectives, indicating that the specific content of environmental information varies significantly among different firms (Wu et al., 2015). Regarding the disclosure channels, firms disclose their environmental performance through official websites, environmental responsibility or sustainable development reports, or annual reports.

However, due to the lack of a clear environmental disclosure framework in China, the environmental information disclosed by firms is not comparable. Furthermore, firms' opportunistic behavior regarding environmental responsibility is not conducive to the acquisition of real information by shareholders, creditors, and potential investors (Radu and Francoeur, 2017). Therefore, effectively improving corporate environmental disclosure is an urgent issue. The extant literature has examined a comprehensive list of factors that influence corporate environmental information disclosure. However, the combined effect of these factors did not receive enough attention. Moreover, the content of the disclosure was not distinguished, leading to biased results. Focusing on heavily polluting firms, this study examines the influence of media attention and state-owned equity on corporate environmental disclosure and their interaction effect. The possible contributions of this study are that we examine: 1) the heterogeneity of the impact of media attention and state-owned equity, as different supervision mechanisms, on corporate environmental information disclosure; and 2) the interaction effect of media attention and state-owned equity on environmental information disclosure.

The remainder of this study is arranged as follows. Section 2 is devoted to the literature review. Section 3 details the theoretical analysis and research hypotheses. Section 4 describes the data source, explains the variable design, and introduces the model. Section 5 outlines the empirical results. Section 6 presents the conclusions, while Section 7 proposes the suggestions.

2 Literature review

Regarding voluntary disclosure of environmental information, an important area of concern is the motivation for corporate environmental information disclosure. These motivations can be divided into internal and external factors. Internal factors include corporate scale, corporate growth, financial leverage, profitability, nature of property rights, corporate governance, and corporate culture, etc. First, let us consider scale and operational factors. Large-scale companies are more active in environmental responsibility efforts and have a higher quality of environmental information disclosure (Lee, 2017). Profitable firms have more environmental governance capital, and thus, are more capable of providing a high level of environmental information disclosure (Qiu et al., 2016). However, some studies find that firms with poor business performance are more inclined to disclose environmental information with no substantive content in order to make up the numbers (Baldini et al., 2018). Firms with high leverage also tend to disclose high-quality environmental information in order to reduce information asymmetry and capital cost (Park and Peng, 2013).

Second, there is the firm's corporate governance. Firms' environmental behaviors can differ depending on the nature of their property rights. For example, compared with private firms, state-owned firms may proactively undertake corporate environmental behaviors (Acar et al., 2021). Ownership concentration is negatively correlated with corporate environmental information disclosure, indicating that majority shareholders and management generally lack the enthusiasm to undertake environmental governance (Chen et al., 2021). In addition, under pressure from public shareholders, companies with a higher proportion of institutional investors will tend to disclose high-quality environmental information to meet the needs of shareholders (D'Amico et al., 2016). Other corporate governance factors like board size and proportion of independent directors are also positively correlated with environmental information disclosure, indicating that good internal governance improves corporate transparency (Liu and Zhang, 2017). Finally, experienced managers can make flexible judgments regarding environmental management, and their environmental information disclosures are also of higher quality (Ma et al., 2019).

Next, external factors include regulatory policies, media attention, industry characteristics, and market competitiveness, among others. Regulatory policies tend to pressure firms to comply with regulations; these firms are more inclined to disclose high-quality environmental information (Barbu et al., 2014; Liu et al., 2021). Firms in developed regions are more active in disclosing environmental information due to stricter regulatory measures (Park and Peng, 2013). Media attention will also bring public pressure on firms; under this pressure, firms are more inclined to disclose environmental information to maintain their reputation (Brammer and Pavelin, 2008; Moroney et al., 2012; Rupley et al., 2012; Meng et al., 2019). In addition, disclosures may vary by industry and market competition. For example, firms in environmentally sensitive industries tend to disclose more environmental information to meet investors′ demands (Lu and Abeysekera, 2014); meanwhile, firms experiencing medium competitive intensity disclose more detailed environmental information to distinguish themselves from their competitors (Delgado-Márquez et al., 2017).

In China's practice, in order to strengthen environmental information disclosure, a series of laws and regulations have been introduced, such as the Guidelines for Environmental Information Disclosure of Listed Companies. These regulations put forward specific requirements for listed companies to accurately, timely, and completely disclose environmental information. Under legal pressure, the number of firms that disclose environmental information has increased, but the quality of their disclosures has not been satisfactory. The disclosures are selective and self-serving: positive and descriptive information that is difficult to verify is quite common, while negative, numerical information is relatively scarce (Xu et al., 2021). When studying the impact of corporate social responsibility (CSR) on corporate performance, Bhattacharyy and Rahman (2019) verified that mandatory laws are an important but not the only determinant of CSR fulfillment (Bhattacharyya and Rahman, 2019). Li (2018) found that environmental information disclosure is widely characterized by "too much expression of strategic planning" and "too little actual practice information". Those firms are better at self-packaging and exaggerating environmental information disclosure (Li, 2018). Clarkson et al. (2008) pointed out that the research on environmental information disclosure should shift from pure level of disclosure to specific content of disclosure. The empirical research results of Acar and Temiz. (2020) showed that the quality of environmental information disclosed by Chinese enterprises is unsatisfactory. It is impossible to distinguish a firm's environmental performance simply through general environmental information disclosure. Therefore, it is necessary to distinguish the content of environmental information.

As we can see, the extant literature has examined a comprehensive list of factors that influence environmental information disclosure. Here, we focus on state-owned equity and media attention. Some scholars have analyzed the influence of these two factors on environmental information disclosure. However, these studies failed to consider the combined effect of both factors on environmental information disclosure and did not distinguish the specific content of the disclosed information. On the one hand, as an external supervision mechanism, media plays an important role in the capital market. The media transmits the operational status of firms to the outside world by disseminating information and influences firms' behavior through the reputation mechanism. Media supervision can promote firms to fulfill their environmental responsibilities better. On the other hand, as government representatives, state-owned firms undertake more environmental responsibilities than non-state-owned ones. The former pay more attention to environmental performance in their operations and tend to promote corporate environmental information disclosure through corporate governance. Thus, media attention and state-owned equity play the roles of external and internal supervision mechanisms, respectively; this can improve the level of corporate environmental information disclosure. Essentially, we ask whether there are differences in the content of environmental information disclosures? Further, what is the interaction effect between media attention and state-owned equity on environmental information disclosure?

To examine these issues, this study distinguished the specific content of environmental information. It tested the impact of media attention, state-owned equity, and their interaction effect on the environmental information disclosure of A-share heavily polluting firms in the Shanghai and Shenzhen stock markets from 2015 to 2019. This study aims to examine: 1) the impact of media attention and state-owned equity, as different supervision mechanisms, on corporate environmental information disclosure; and 2) the interaction effect of media attention and state-owned equity on environmental information disclosure. The results of this paper not only supplement the existing literature but also provide policy support for promoting firms to fulfill their environmental responsibility better.

3 Research hypotheses

While pursuing economic interests, firms also shoulder the social responsibility of protecting the environment. Under information asymmetry, media attention can act as an informal external governance mechanism. Further, it can help in effectively supervising firm behavior and even force firms to fulfill their social responsibilities. As their reputation hinges on it, firms convey good news to the market through the appropriate disclosure of environmental information; this helps establish their positive image as a firm with a good environmental management system.

Indeed, Kuo and chen, (2013) found that the public learned about firms' environmental systems and their implementation mainly through environmental news. The authors noted that as the primary way of information acquisition, media affected corporate image; consequently, voluntary disclosure of environmental information by firms in social responsibility reports is conducive to improving their social status. Aerts et al. (2008) also showed that firms with high media attention feel pressured by public opinion. Again, the authors found that firms are more proactive in disclosing environmental information to gain social recognition. Notably, the number of ex-post reports on environmental information significantly impacts corporate environmental information disclosures more than prior reports. Using samples of environmentally sensitive industries, Zhou et al. (2022) confirmed that increased community pressure is negatively associated with corporate pollution levels, and thus, positively associated with corporate environmental performance. Kong et al. (2020) reviewed the literature and pointed out that media attention induces firms to exert more effort on environmental protection, especially when there are adverse media reports. Xue et al. (2021) empirically found that both media attention and government regulation were significantly positively correlated with environmental information disclosure; notably, the more adverse the effect of government regulation, the more media attention promotes environmental information disclosure. Based on the above analysis, we propose the following hypothesis:

Hypothesis 1: *Media attention has a positive impact on corporate environmental information disclosure.*

Shareholders can significantly affect a firm's behavior. Intuitively, controlling shareholders can positively affect firm performance and operational efficiency commitment to environmental friendliness (Utomo et al., 2018). Interestingly, some studies report that the shareholding ratio of state-owned shareholders is correlated with company performance (Lin et al., 2020). Specifically, compared with non-state-owned firms, state-owned firms must undertake more environmental protection efforts on behalf of their country and society because of their particular political status, and consider political, social, and economic interests.

Furthermore, state-owned enterprises themselves have high social attention. Under the pressure of social supervision, they can play an exemplary role in environmental information disclosure. Zhang et al. (2022) found that CSR activities improve when the proportion of state-owned capital in a private-holding listed company exceeds 5%. Using a sample of 140 countries, Mahjoub and Amara (2020) confirmed a notable positive effect of shareholder governance on environmental sustainability. Calza et al. (2016) found a positive correlation between firms' performance on environmental activities and their state ownership percentage. Specifically, compared with non-state-owned firms, state-owned firms performed better on environmental responsibility.

Therefore, state-owned equity can have a "governance effect"; the higher the proportion of state-owned equity, the higher the degree of government participation in corporate governance and the higher the level of environmental information disclosure of firms. Data from China Listed Companies′ Environmental Responsibility Information Disclosure Evaluation Report (2020) showed that the level of environmental information disclosure of state-owned firms is much higher than that of non-state-owned firms. Based on the above analysis, we propose our second hypothesis:

Hypothesis 2: *State-owned equity has a positive impact on corporate environmental information disclosure.*

As argued before, both media attention and state-owned equity can help govern firms' environmental behavior externally and internally, respectively. However, the effects of these two factors may be substitutable. When the proportion of state-owned equity is low, its internal influence on firm governance will be low, and information asymmetry and agency problems will be prominent; this may trigger other alternative mechanisms to supervise corporate behavior. Then, as an important form of informal governance and extra-legal system, media attention can replace the supervisory function of state-owned equity and address weak corporate governance.

Huang et al. (2020) confirmed that media attention and state-owned equity have a substitution effect on firms' targeted poverty alleviation behavior. For firms with low degree of state-owned equity, media attention has a more significant impact on firms' willingness to participate in targeted poverty alleviation efforts. Yang et al. (2020) noted that under media attention, non-state-owned firms are more active in disclosing environmental information. Guo and Lu (2020) observed that the impact of media on corporate environmental performance is more obvious in areas where the government pays less attention to environmental protection; however, in other areas, this impact is not clear.

In summary, compared with firms with high state-owned equity, those with low state-owned equity have less environmental supervision from state-backed shareholders and are more likely to commit environmental violations and attract media attention. Then, under the pressure of public opinion, firms are urged to disclose more environmental information to recover their reputation losses. Meanwhile, for firms with high state-owned equity, government pressure will promote corporate environmental information disclosure and there may be fewer chances for media to exert their external governance function. Based on this, we propose our third and final hypothesis:

Hypothesis 3: *There is a substitution relationship between state-owned equity and media attention on the impact of environmental information disclosure.*

TABLE 1 Environmental information disclosure indicators and scoring rules.

Classification of content	Disclosure indicators	Non-disclosure	Qualitative disclosure	Qualitative and quantitative disclosure
Financial environmental information disclosure (FEDI)	Expenditure on sewage discharge	0	1	2
	Environmental protection investment	0	1	2
	Emergency expenditure for major environmental problems	0	1	2
	Benefits from reducing pollution	0	1	2
	Income from the use of waste	0	1	2
	Environmental subsidies or awards	0	1	2
Non-financial environmental information disclosure (NFEDI)	Environmental information disclosure system	0	1	2
	Environmental management system	0	1	2
	Environmental protection measures and improvement	0	1	2
	Pollutant types and emissions	0	1	2
	Energy saving measures and results	0	1	2
	Environmental certification	0	1	2
	Independent environmental report or social responsibility report	2 for independent report, 0 otherwise		

4 Research design

4.1 Data sources

We use data on A-share listed firms in heavily polluting industries in the Shanghai and Shenzhen stock markets from 2015 to 2019. After excluding listed companies with abnormal financial and missing data, 2,409 sample data were finally collected. The environmental information disclosure index (EDI) is graded manually from annual reports, social responsibility reports, and official websites. Media attention data from China Research Data Service (CNRDS) and other data from the RESSET database. To eliminate the impact of outliers, all continuous variables were winsorized at 1% and 99% levels. Finally, Stata 15.0 was used for data processing and analysis.

4.2 Variable design

4.2.1 Explained variable

The explained variable is the environmental information disclosure index (EDI). Following Wu et al. (2015), this study uses content analysis, the most common method, to calculate EDI. EDI was calculated from 13 indicators, including 6 financial and 7 non-financial environmental information disclosure indicators. The full score for each indicator is 2 points, with 0 points for non-disclosure, 1 point for qualitative disclosure, and 2 points for both qualitative and quantitative disclosure. Table 1 lists the indicators and scoring rules.

To avoid subjectivity, each item is given the same weight. The formulae of EDI, financial EDI (FEDI), and non-financial EDI (NFEDI) are listed below. A higher index value indicates a higher quality of environmental information disclosure.

$$EDIF_{\mathrm{it}} = \frac{\sum_{j=1}^{6} SCID_{ijt}}{6} \times 100 \tag{1}$$

$$EDINF_{\mathrm{it}} = \frac{\sum_{j=7}^{13} SCID_{ijt}}{7} \times 100 \tag{2}$$

$$EDI_{\mathrm{it}} = EDIF_{\mathrm{it}} + EDINF_{\mathrm{it}} \tag{3}$$

where t represents the year, i represents the firm, j represents the disclosure indicator, and $SCID_{ijt}$ represents firm i's score on indicator j in year t.

4.2.2 Explanatory variables

The explanatory variables were media attention and state-owned equity. Media attention can be measured by the number of network or newspaper media reports. This study chooses newspaper media reports because they are highly original, authentic, and authoritative (Zyglidopoulos et al., 2012). The natural logarithm of "number of newspaper reports + 1" is used to express the degree of media attention. The higher the value, the higher the media attention. Regardless of the tendency of the report, media reports will attract stakeholders' attention to the reported firms. Therefore, we do not distinguish the content of media reports further. Next, referring to Song and song (2015), state-owned equity is calculated by dividing the number of state-owned shares by the total number of shares.

TABLE 2 Variable definition.

Variable symbol	Definition	Calculation method
EDI	Environmental information disclosure index	The score of EDI that calculated in Section 4.2.1
FEDI	Financial environmental information disclosure index	The score of EDIF that calculated in Section 4.2.1
NFEDI	Non-financial environmental information disclosure index	The score of EDINF that calculated in Section 4.2.1
Media	Media attention	Ln (number of newspaper reports+1)
State	State-owned equity	Number of state-owned shares/total number of shares
Size	Firm size	Ln (total assets)
ROA	Return on total assets	Net profit/average total assets
Lev	Asset-liability ratio	Total liabilities/total assets
Growth	Assets growth rate	(Total assets this year–total assets last year)/total assets last year
Own5	Ownership concentration	Number of shares of the top 5 shareholders/total number of shares
IndPct	Proportion of independent directors	Number of independent directors/number of total directors

4.2.3 Control variables

Following previous research (Lu and Abeysekera, 2014; Kouloukoui et al., 2019; Luo et al., 2019; Wasara and Ganda, 2019), our control variables include firm size, return on total assets, asset-liability ratio, assets growth rate, ownership concentration, and proportion of independent directors. The definition and calculation method of variables are shown in Table 2.

4.3 Estimation models and methods

We use the following estimation models for hypothesis testing:

$$\mathrm{EDI}_{it}\left(\mathrm{FEDI}_{it}, \mathrm{NFEDI}_{it}\right) = \beta_0 + \beta_1 \mathrm{Media}_{it} + \sum_{i=1}^{6} \gamma_i \mathrm{Control}_{it} + \xi_{it} \tag{4}$$

$$\mathrm{EDI}_{it}\left(\mathrm{FEDI}_{it}, \mathrm{NFEDI}_{it}\right) = \beta_0 + \beta_1 \mathrm{State}_{it} + \sum_{i=1}^{6} \gamma_i \mathrm{Control}_{it} + \xi_{it} \tag{5}$$

$\mathrm{EDI}_{it}\left(\mathrm{FEDI}_{it}, \mathrm{NFEDI}_{it}\right) = \beta_0 + \beta_1 Media_{it} + \beta_2 \mathrm{State}_{it} + \beta_3 Media_{it} * \mathrm{State}_{it} + \sum_{i=1}^{6} \gamma_i \mathrm{Control}_{it} + \xi_{it}$ Where Media represents the media attention, State represents state-owned equity, Control represents the six control variables, β and γ are the coefficient estimates of these explanatory and control variables, respectively, ε represents the random disturbance term, i represents the sample firm, and t represents the year.

As panel data were used, the Hausman test was conducted on all models; the resulting *p* values are all less than 0.01, rejecting the hypothesis of random effect. Therefore, this study adopts the fixed effect model to perform regression analysis with the above three models. Although the Hausman test supports the fixed effect model, it has a strict assumption that the explanatory variables do not correlate with the random disturbance term. It will lead to an endogeneity problem if this assumption is not met. Here, we assume that the models in this paper satisfied the assumption that the explanatory variables are exogenous and uncorrelated with the random disturbance term.

TABLE 3 Descriptive statistics of variables.

Variable	Obs	Mean	Std. Dev	Min	Max
EDI	2,409	1.614	0.748	0.143	3.524
FEDI	2,409	0.806	0.388	0	1.833
NFEDI	2,409	0.808	0.445	0.143	1.714
Media	2,409	3.440	1.281	0.693	7.095
State	2,409	0.031	0.104	0	0.788
Size	2,409	22.600	1.332	20.083	26.331
ROA	2,409	0.048	0.074	-0.674	0.430
Lev	2,409	0.401	0.194	0.059	0.843
Growth	2,409	0.119	0.209	-0.262	1.034
Own5	2,409	0.536	0.152	0.106	0.949
IndPct	2,409	0.362	0.091	0.114	0.714

5 Empirical results

5.1 Descriptive statistics

Table 3 shows the descriptive statistics. EDI has mean, maximum, and minimum values of 1.614, 3.524, and 0.143, respectively. This indicates that the level of environmental information disclosure in heavily polluting industries in China is much lower than the total score of 4. The maximum value of FEDI was 1.833 and slightly higher than that of NFEDI at 1.714. Generally, financial environmental information is easier to disclose quantitatively. However, the average FEDI is lower than that of NFEDI at 0.806 versus 0.808. Thus, firms may have a slightly stronger tendency to disclose non-financial environmental information.

TABLE 4 Variable correlation coefficients.

	EDI	FEDI	NFEDI	Media	State	Size	ROA	Lev	Growth	Own5	IndPct
EDI	1										
FEDI	0.878***	1									
NFEDI	0.909***	0.600***	1								
Media	0.257***	0.148***	0.302***	1							
State	0.079***	0.095***	0.052**	0.050**	1						
Size	0.513***	0.388***	0.523***	0.466***	0.165***	1					
ROA	-0.046**	-0.080***	-0.006	0.148**	-0.0120	-0.0290	1				
Lev	0.293***	0.293***	0.237***	0.128***	0.119***	0.483***	-0.395***	1			
Growth	-0.175***	-0.159***	-0.154***	0.046**	-0.041**	-0.086***	0.375***	-0.105***	1		
Own5	0.116***	0.047**	0.154***	0.229***	0.232***	0.365***	0.147***	0.0290	0.051**	1	
IndPct	-0.089***	-0.058***	-0.101***	-0.092***	-0.141***	-0.183***	-0.00100	-0.101***	0.076***	-0.118***	1

Note: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively.

TABLE 5 Regression results of Media and EDI.

Variables	I	II	III
	EDI	FEDI	NFEDI
Media	0.0541***	0.00755	0.0468***
	(5.240)	(1.264)	(7.324)
Size	0.231***	0.0887***	0.142***
	(18.98)	(12.10)	(19.68)
ROA	0.242	0.125	0.122
	(0.976)	(0.871)	(0.867)
Lev	0.294***	0.277***	0.0174
	(3.543)	(5.813)	(0.359)
Growth	-0.312***	-0.153***	-0.158***
	(-5.125)	(-4.422)	(-4.453)
Own5	-0.223**	-0.162***	-0.0565
	(-2.531)	(-3.186)	(-1.091)
IndPct	0.0555	0.0715	-0.0253
	(0.391)	(0.889)	(-0.308)
Constant	-3.894***	-1.340***	-2.536***
	(-15.22)	(-8.592)	(-17.03)
Observations	2,409	2,409	2,409
R-squared	0.378	0.244	0.382
Prob > F	0.0000	0.0000	0.0000

Note: *t* statistics are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively.

Next, the mean, maximum, minimum values, and standard deviation of Media are 3.44, 7.095, 0.693, and 1.281, respectively. This indicates that while media pays high attention to firms on average, this attention varies substantially. Finally, the mean, maximum, and minimum values of state-owned equity are 0.031, 0.788, and 0, respectively. Thus, state shareholding in heavily polluting firms is relatively low and most of these firms are private.

5.2 Correlation test

Pearson correlation coefficients of variables are shown in Table 4. Media is positively and significantly correlated with EDI, FEDI, and NFEDI, at the 1% level. This indicates that firms with high media attention have a higher level of environmental information disclosure, which preliminarily supports Hypothesis 1. Next, State has significantly positive correlations with EDI, FEDI, and NFEDI at the 1% level. Thus, firms with a higher proportion of state-owned equity have a higher level of environmental information disclosure, which preliminarily supports Hypothesis 2. Except for the explained variables, the maximum coefficient between all variables is 0.523. This indicates that there is no serious multicollinearity between variables and our model is suitable for further multiple regression analysis.

5.3 Regression analysis

5.3.1 Media and EDI

Columns I–III in Table 5 list the regression results of Media with EDI, FEDI, and NFEDI, respectively. The R^2 of the three models are 0.378, 0.244, and 0.382, respectively, and the F statistic value is significant at the 1% level, indicating that the model fits well. According to Column I, Media is significantly and positively correlated with EDI at the 1% level. This indicates that media attention has a positive impact on environmental information disclosure. The more media attention a firm receives, the higher the level of its environmental disclosure. Thus, Hypothesis 1 is supported.

However, after classifying the content of environmental information, media attention only has a significant impact on NFEDI at the 1% level, but has no significant impact on FEDI. This indicates that the higher the media attention, the more firms

TABLE 6 Regression results of State and EDI.

Variables	I	II	III
	EDI	FEDI	NFEDI
State	0.225*	0.257***	-0.0295
	(1.725)	(3.807)	(-0.344)
Size	0.257***	0.0916***	0.164***
	(22.42)	(13.22)	(24.98)
ROA	0.418*	0.155	0.269*
	(1.687)	(1.078)	(1.918)
Lev	0.267***	0.264***	0.00348
	(3.175)	(5.526)	(0.0706)
Growth	-0.310***	-0.149***	-0.161***
	(-5.026)	(-4.289)	(-4.399)
Own5	-0.246***	-0.195***	-0.0468
	(-2.740)	(-3.764)	(-0.884)
IndPct	0.0798	0.100	-0.0296
	(0.558)	(1.246)	(-0.355)
Constant	-4.459***	-1.396***	-3.046***
	(-18.45)	(-9.420)	(-22.46)
Observations	2,409	2,409	2,409
R-squared	0.373	0.247	0.369
Prob > F	0.0000	0.0000	0.0000

Note: *t* statistics are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively.

TABLE 7 Regression results of Media, State, and EDI.

Variables	I	II	III
	EDI	FEDI	NFEDI
Media	0.0566***	0.00883	0.0479***
	(5.459)	(1.469)	(7.537)
State	0.285**	0.268***	0.0189
	(2.091)	(3.844)	(0.213)
Media*State	-0.178**	-0.0401	-0.139**
	(-2.015)	(-0.894)	(-2.479)
Size	0.228***	0.0872***	0.141***
	(18.82)	(11.94)	(19.56)
ROA	0.222	0.123	0.104
	(0.893)	(0.855)	(0.739)
Lev	0.288***	0.268***	0.0211
	(3.457)	(5.600)	(0.433)
Growth	-0.305***	-0.148***	-0.157***
	(-5.007)	(-4.265)	(-4.398)
Own5	-0.252***	-0.195***	-0.0525
	(-2.814)	(-3.769)	(-1.001)
IndPct	0.0979	0.104	-0.0151
	(0.691)	(1.293)	(-0.184)
Constant	-3.837***	-1.299***	-2.519***
	(-15.03)	(-8.352)	(-16.92)
Observations	2,409	2,409	2,409
R-squared	0.380	0.248	0.384
Prob > F	0.0000	0.0000	0.0000

Note: *t* statistics are in parentheses. ***, **, and * indicate statistical significance at the 1, 5%, 5%, and 10% levels, respectively.

are inclined to improve their disclosure of non-financial environmental information. One possible explanation is that firms with high media attention are under high social pressure, which prompts them to disclose more environmental information. However, such disclosure is a passive behavior; its purpose is not to improve the environmental responsibility and rather show off their environmental responsibility. Since financial information is difficult to fabricate in a short time, firms will respond to media attention by disclosing more non-financial information without substance.

5.3.2 State and EDI

Columns I–III in Table 6 list the regression results of State with EDI, FEDI, and NFEDI, respectively. The R^2 of the three models are 0.373, 0.247, and 0.369, respectively, and the F statistic value is significant at the 1% level, indicating that the model fits well. According to Column I, State is positively and significantly correlated with EDI at the 10% level, indicating that state-owned equity has a positive impact on environmental information disclosure. Firms with higher state-owned equity perform better at environmental information disclosure. Thus, Hypothesis 2 is supported.

Comparing the content of environmental information in columns II and III shows that state-owned equity only has a positive and significant impact on financial environmental information disclosure at the 1% level; the impact on non-financial environmental information disclosure is not significant. This indicates that the higher the proportion of state-owned equity, the higher the disclosure level of financial environmental information. One possible explanation is that state-owned equity has governance effects on firms as the state-backed shareholders' supervision internally pressures firms to bear social responsibilities, which internally drives firms' pro-environmental behavior. Therefore, firms are more active in fulfilling their environmental responsibilities. Moreover, rather than just making superficial as under media attention, they will disclose more financial information that cannot be easily manipulated to distinguish themselves from other firms.

5.3.3 Media, state, and EDI

Table 7 incorporates Media, State, and their interaction into the same regression model for testing. To reduce the multicollinearity between State and State*Media as well as between Media and State*Media, Media and State have been centralized before the regression. The R^2 of the three models are 0.380, 0.248, and 0.384, respectively, and the F statistic value is

TABLE 8 Robustness test.

Variables	Robustness test I			Robustness test II			Robustness test III		
	EDI	FEDI	NFEDI	EDI	FEDI	NFEDI	EDI	FEDI	NFEDI
Media	0.0258**	0.0087	0.0404***	0.0607***	0.0096	0.0513***	0.0552***	0.0079	0.0474***
	(1.979)	(1.030)	(4.475)	(5.575)	(1.517)	(7.723)	(5.305)	(1.315)	(7.423)
State	0.344***	0.277***	0.0045	0.122**	0.0953***	0.0280	0.284**	0.276***	0.0102
	(2.896)	(3.769)	(0.0479)	(2.475)	(3.709)	(0.858)	(2.028)	(3.851)	(0.112)
Media*State	-0.117	-0.0358	-0.101	-0.0773***	-0.0257	-0.0521**	-0.173*	-0.0360	-0.138**
	(-1.536)	(-0.559)	(-1.261)	(-2.622)	(-1.641)	(-2.542)	(-1.942)	(-0.796)	(-2.445)
Observations	2,409	2,409	2,409	2,409	2,409	2,409	2,079	2,079	2,079
R-squared	0.566	0.245	0.372	0.378	0.245	0.381	0.377	0.246	0.381
Prob > F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

significant at 1% level, indicating that the model fits well. According to Column I, the coefficient of Media and State is positive and significant at the 1% and 5% levels, respectively. Meanwhile, the coefficient of State*Media is negative and significant at the level of 5%, implying a substitution effect between Media and State. That is, media attention is more likely to play a supervisory role when the proportion of state-owned equity is low. By contrast, a higher proportion of state-owned equity already plays a sufficient internal supervisory function; then, the additional effect of media attention may not be obvious. That is, high state-owned equity can weaken the positive effect of media attention on corporate environmental information disclosure. Thus, Hypothesis 3 is supported.

Again, comparing the indicators of environmental information in columns II and III shows that the substitution effect of media attention and state-owned equity exists only in non-financial environmental information disclosure. This may be because during the measurement, recording, and disclosure of financial information, firms must comply with accounting standards. Consequently, the space for manipulation is limited. Meanwhile, the disclosure of non-financial environmental information is more flexible. This information includes written descriptions, such as policy introductions and system descriptions as well as charts or pictures; these can be easily controlled by firms. When the proportion of state-owned equity is low, firms that receive more media attention will more actively disclose environmental information under public pressure. However, as manipulating financial environmental information is difficult, firms will tend to avoid including monetized data that are difficult to fake. Instead, firms will choose to disclose more non-monetary environmental data that is descriptive, non-substantive, and easily manipulable. Therefore, the substitution effect of state-owned equity and media attention is mainly reflected in non-financial environmental information.

In addition, firm size, ROA, and leverage are positively related to EDI, indicating that firms with large size, strong profitability, and high leverage are more active in environmental disclosure. The empirical results are consistent with the existing literature. Large-scale companies have a higher quality of environmental information disclosure due to their rich experience (Lee, 2017). Profitable firms have more environmental governance capital, and thus, are more capable of providing a high level of environmental information disclosure (Qiu et al., 2016). Firms with high leverage also tend to disclose high-quality environmental information in order to reduce information asymmetry and capital cost (Park and Peng, 2013).

In contrast, growth rate and ownership concentration are negatively related to EDI, indicating that firms with rapid growth and concentrated ownership are more passive in environmental information disclosure. The explanation for the results is that fast-growing firms do not have enough energy for environmental management, and majority shareholders and management generally lack the enthusiasm to undertake environmental governance (Chen et al., 2021). The empirical results are consistent with our expectations.

5.4 Robustness test

To ensure the reliability of our findings, we conducted the following robustness tests. First, the natural logarithm of "number of network reports + 1" was used to measure the explanatory variable Media Attention. Second, the dummy variable "whether state-owned enterprises" was used to replace the variable State-owned Equity. Finally, we performed repeatability test on the remaining samples after randomly deleting some samples. The results of the above tests showed that our findings qualitatively remained the same, indicating that our research is robust. The results of the robustness test are shown in Table 8.

6 Conclusion and limitations

6.1 Conclusion

This study empirically examines the influence of media attention and state-owned equity on environmental information disclosure using data on A-share heavily polluting firms in the Shanghai and Shenzhen stocks markets from 2015 to 2019. Our empirical results are as follows:

First, media attention can play an external supervisory role in corporate environmental information disclosure. However, this supervision only seems effective for non-financial environmental information and the effect on financial environmental information is not obvious. This may be because compared with financial environmental information, which is constrained by accounting standards, the disclosure of non-financial environmental information is more arbitrary, subjective, and manipulatable. Therefore, under external pressure such as media opinion and public pressure, firms will then choose to manipulate non-financial environmental information and disclose more information with no substantive content.

Second, state-owned equity plays an internal governance role in the disclosure of enterprise environmental information. Firms with a high proportion of state-owned equity have a higher level of environmental information disclosure, which is mainly reflected in financial environmental information. This shows that when firms are under the supervision of state shareholders, they will have the internal driving force of environmental responsibility and the urge to take more substantive measures to fulfill their environmental responsibilities, rather than just superficial efforts in text. The results showed the heterogeneity of the impact of media attention and state-owned equity, as different supervision mechanisms, on corporate environmental information disclosure.

Third, media attention and state-owned equity supervise corporate environmental responsibility externally and internally in firms, respectively; importantly, the two have a substitution effect on environmental information disclosure, which is mainly reflected in non-financial information disclosure. When the proportion of state-owned equity is low, supervision from state-owned shareholders is insufficient, and the level of environmental information disclosure is low. Then, when these firms receive high media attention, they will actively disclose environmental information, especially non-financial information, to improve their "green" image. Meanwhile, when the proportion of state-owned shares is high, the supervision from state-owned shareholders induces firms to pay more attention to environmental information and responsibilities. Therefore, greater media scrutiny has no apparent effect on improving the environmental information disclosure and cannot further strengthen the firms' motivation regarding disclosures. The results imply the substitution effect of media attention and state-owned equity on environmental information disclosure.

6.2 Limitations

There are still some problems worth further discussion in this research, mainly in the following three aspects: Firstly, in terms of the influence mechanism of media attention and state-owned equity on corporate environmental information disclosure, in addition to the moderator factors discussed in this paper, there may be some mediating factors that need further study. Second, in terms of sample selection, the research samples in this paper only include polluting firms. Non-polluting firms should also undertake environmental responsibilities, and the study needs to expand research samples in the future. Third, the fixed effect model has several limitations, and it may not actually be the best method in this paper, which may cause endogeneity problems. Instrumental variables can be considered to deal with endogeneity issues in the future.

7 Suggestions

First, the government should allow media to fully leverage their external supervisory role, and use media to increase the pressure on firms to fulfill their environmental responsibilities. However, media reports should be authentic, reliable, independent, and fair. Furthermore, there should be more attention on firms' practical and effective environmental responsibility behaviors/efforts to prevent them from greenwashing with empty slogans, and guide investors to pay attention to firms' substantive environmental performance.

Second, state-owned equity is a suitable supervision mechanism for environmental information disclosure. Firms should give full play to the role of state-owned shareholders in corporate governance. State-owned firms should set an example of environmental responsibility and guide other firms to perform environmental responsibility better.

Third, environmental accounting standards should be further improved and environmental information disclosure standards should be clarified to improve the standardization of environmental information disclosures. Enhancing the comparability of environmental information across firms is vital to reduce discretion and subjectivity in environmental information disclosures.

Last, firms should improve the level of environmental information disclosures according to their own characteristics. Firms with a low level of state-owned equity should focus on improving the construction of environmental protection facilities, increasing R&D and pollution-control investments, and effectively improving their substantive environmental

performance. Meanwhile, firms with a high degree of state-owned equity participation should work on publicizing their pro-environmental efforts and actively disclose their environmental management information through their official website or press conferences; this will help enhance the social recognition of their corporate environmental responsibility efforts.

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.

Author contributions

F L: writing, data collection and review QC: writing draft, conclusion, revision, English corrections, and Discussion L X: Data, analysis, review, improve, concept J W: Introduction, Methods and Data analysis LV: review, editing, discussion, implications.

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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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Teleworking in Romania during Covid-19 crisis: From conjunctional adaptation to change of economic paradigm

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The COVID-19 crisis has led to a raise in the number of people working remotely. This paper aims at identifying the extent to which the pandemic will determine a paradigm change regarding teleworking in Romania Our research is based on two surveys designed to assess the impact of teleworking both on individuals and on efficiency at the organizational level. The results show that, generally, teleworking has significant advantages, both for employees and employers. As we become aware of these advantages, it is quite likely that Romania will experience a paradigm shift in terms of teleworking, as both managers and employees consider that teleworking becomes a very good option. However, the changes will be gradual and with different intensities at the sectoral level, as teleworking must be adapted to the specificities of each sector or activity. While some sectors tend to make teleworking the new organizational culture, others will capitalize on the benefits of teleworking progressively, in relation to technological endowments and structural changes that will continue to occur. On the other hand, teleworking has the advantage of promoting the improvement of digital skills for employees, which is a great step forward for a higher degree of digitisation.

KEYWORDS

teleworking, survey, digitalization, crisis, paradigm shift

1 Introduction

The COVID-19 crisis is already a major challenge for the global economy, but also in terms of economic policy decisions. Sooner or later, we may find that the crisis-induced adjustments will indicate profound disruptive effects on the current economic model, that is, anyway, in an obvious transition to the digital economy and society.

In the future, disruptive trends will become the norm for many of today's sectors, which will be reconfigured either by vision or by the imperative of adaptation, under the pressure of digital innovations and technologies. Therefore, opportunities for adjustment and modernization can and must be identified in the corona-crisis equation.

In essence, the COVID-19 crisis could reshape the industrial and commercial structure on a global scale, could restructure the price system, the investment geography, human capital and, perhaps most importantly, the trade and mobility system that currently defines the order of economic globalization.

In Romania, in order to limit the spread of the SARS-COV-2 virus among the population, alike most countries of the World, a series of unprecedented restrictions were adopted (Official Journal of Romania, 2020) which had a great impact on the economy as a whole, on the labor market and on people`s social lives. While the pandemic had a great impact on certain economic sectors, which were more likely to be affected by the restrictions (such as HORECA—hospitality - or tourism services), other sectors had the advantage of being able to change their strategy regarding the way of working, by offering the employees the solution of teleworking (Vasilescu, 2021).

Even if stay at home restrictions will be gradually replaced by stay safe ones, teleworking, video conferences, protection and social distance measures will continue to be part of our daily lives. Maybe some will even become business opportunities or new paradigms in social life.

Before the pandemic, Romania registered almost the lowest percentage of employed persons that were usually working from home in the European Union (only Bulgaria had an even lower percentage—Figure 1) and, of course, almost the higher percentage of employed persons that never used to work from home (98.6%). Even though the percentages are very low, women seemed to be more likely to work from home on a regularly basis (usually), compared to men (1.1% of the employed women, compared to only 0.5% of the employed men) (Eurostat, 2021).

However, the restrictions adopted alongside with the pandemic, have led to an increasing number of people working from home in Romania, both in large and small private companies, but also in the public sector (Vasilescu, 2021).

As the readiness of countries to shift to teleworking can be measured by the level of digital skills, given that the more digitalised a country was prior to the pandemic, the more likely workers were to start teleworking in the context of the pandemic, and therefore the more societally resilient the member state was, it is considered that Romania lacked this readiness (European Economic and Social Committee, 2021).

Under these circumstances, we consider it important to assess the impact of this new situation both on employees and on firm/organizational efficiency. In particular, we aim at identifying the position of Romanian employees and employers/managers on teleworking, to diagnose the real situation of teleworking alongside the pandemic.

Also, we consider it important to assess how the Romanian employees and employers relate to the advantages and disadvantages of teleworking and what is the willingness to continue the telework activity and in the aftermath of the pandemic. We deem that the context of the pandemic might lead to a change of the paradigm regarding teleworking and therefore we might see growing numbers of the employed persons practicing it.

Given that, we consider that our paper will contribute significantly to the literature. First, due to the fact that the literature is rather scarce (given the rare incidence of teleworking in Romania), and second, given the way our paper relates to teleworking, considering a paradigm change determined by the COVID-19 crisis. Moreover, our analysis assesses the views about teleworking and its estimated impact for a broader spectrum of stakeholders. First, our respondents work both in the private and the public sectors. Second, the sample includes both managers/employers and employees, in order to have a complete image of its effects. Third, we also assess the impact of teleworking in the educational field, as online

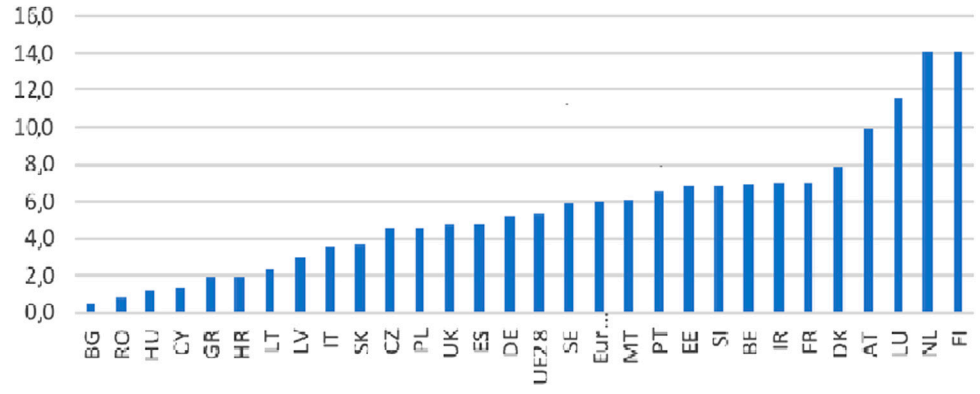

FIGURE 1
Employed persons usually working from home (% of total population 15–64 years, 2019).

schooling was much debated in the context of the changes imposed by the pandemic.

The remainder of the paper is extended as follows: section 2 provides a brief review of the literature. Section 3 describes the research methodology and the data used in this research. Section 4 presents the results. Section 5 presents the discussions of the study.

2 Literature review

The literature regarding teleworking in Romania is rather scarce, mostly due to the fact that this kind of working did not use to be very common. Therefore, regulations regarding teleworking have been issued specifically only late, in 2018 (Dima et al., 2019). Teleworking is defined as a form of work's organization through which the employee, regularly and voluntarily, performs his duties specific to his position, occupation or profession, elsewhere than the workplace organized by the employer, at least 1 day per month, using information technology and communications (Romanian Parliament, 2018).

Even though the COVID-19 crisis is a very recent event and several statistics are still unavailable for assessing its impact on the labor market, on the economy or on the society as a whole, given the fact that this is an unprecedented crisis in the recent history, with a great impact on people`s lives, researchers have showed a great interest for detecting all kinds of details regarding it.

European Economic and Social Committee (2021) investigated how telework and information and communication technology-based mobile work has shaped the behavior of European Union workforce during COVID-19 from the perspective of European trade unios. According to the Committee, the differentiated preparedness of member states created unequal opportunities for the workforce as they had uneven access to digital means and specific digital training. Moreover, teleworking enabled them to seek novel opportunities regardless of timing and location. The study argues that democratic values and overall trust in the national government are part and parcel of the workforce's satisfaction.

According to the literature, teleworking has relevant effects both on job performance and on the organizational performance (Calmels et al., 2021; Davidescu et al., 2020; National Institute of Administration, 2020; Lefter et al., 2017; Serban, 2012). Calmels et al. (2021) obtained that, in France, labour productivity increased by 22% during the pandemic crisis, due to teleworking.

Moreover, some studies have revealed, both in the past and recently, that teleworking is positively associated with work-life balance (Gregg, 2011; Tremblay and Thomsin, 2012; Lopes et al., 2014; Dima et al., 2019; Davidescu et al., 2020; Calmels et al., 2021). Dima et al. (2019) concluded that telework could contribute to a better work-life balance and could generate sustainable effects targeting the long-term management of workforce, providing solutions to potential problems at local community levels. They evaluated the individual and social implications of telework, along with the foreseeable permanent result that could be generated, using a survey carried out on a sample of 1,180 Romanian employees.

Davidescu et al. (2020) obtained that the mix between working from home and working in a company's office is considered an optimal solution in increasing organizational performance, social and professional relationships, learning and personal development and the overall level of work motivation. The authors investigated the link between employee development and worktime and workspace flexibility, job satisfaction and job performance among Romanian employees in order to identify how to redesign human resource management in the context of pandemic crisis using a survey on 220 people.

A challenge for teleworking is the legal part and there are several studies that focus on this aspect (Prosser, 2011; Pyoria, 2011; Popescu, 2018; Belzunegui-Eraso and Erro-Garces, 2020; National Institute of Administration, 2020; European Economic and Social Committee, 2021).

The National Institute of Administration (2020) evaluated the opportunity to regulate different flexible ways of working (telework, flexible schedule, hybrid system and so on) in the Romanian public administration using two questionnaires addressed to executive and management positions in the context of pandemic crisis. The result of the study states that flexible work schemes ensure a better work-life balance, conducting to a higher productivity from employees. The main challenges regarded technical, social, informational and procedural aspects.

European Economic and Social Committee (2021) argue that a uniform basis of rights at the EU level would support the normalisation of telework as an alternative to the traditional organisation of work, with an added value of decent and quality working conditions. Belzunegui-Eraso and Erro-Garces (2020) combined the legal, environmental and security factors that explain teleworking, demonstrating the lack of contingency plans in companies for responding to external factors (such as COVID-19 crisis) that imply a reorganization of work.

Other studies are focusing on the impact of teleworking on gender roles (Giovanis, 2018; Alon et al., 2020; Avdiu and Nayyar, 2020; Hupkau and Petrongolo, 2020; Kristal and Yaish, 2020; Lopez-Igual and Rodriguez-Modrono, 2020; Calmels et al., 2021). Some papers show an increase in gender inequality during the pandemic due to the increase in care work done by women, while other studies obtained an equalization of gender roles, as during lockdown a certain distribution of domestic tasks has been observed. Lopez-Igual and Rodriguez-Modrono (2020) analysed the new profiles of teleworkers, by examining the main factors that increase or decrease the likelihood of different telework and mobile work arrangements, based on information and communication

technology. They analysed a survey based on 20,000 workers in EU15 area and confirmed the heterogeneity in the profiles of workers. According to the authors, occasional teleworkers are usually man managers or professionals, but home-based teleworking is also spreading into more precarious, temporary and lower-paid jobs.

Avdiu and Nayyar (2020) analysed the vulnerability of jobs to social distancing, even in the context of lifting lockdown restrictions, by measuring the importance of face-to-face interactions with consumers. The results show that industries vary in whether they emphasize face-to-face interactions or home-based work and the two do not always go hand-in-hand. The authors found that occupations that are more intensive in face-to-face interaction are largely concentrated among lower wage deciles. Moreover, a large share of women's employment is accounted for by occupations that are intensive in face-to-face interactions.

Some studies research the work pressure generated by teleworking. For example, Thulin et al. (2019) examined how changing conditions for home-based telework affect the quality of life and social sustainability of workers in terms of time pressure and time use control in everyday life, using a survey on a sample of 456 home-based teleworkers employed by six governmental agencies in Sweden. The authors concluded that time pressure is not associated with job type in terms of distinguishing between bounded case work and more independent analytical work.

Time pressure is intensified by family-related factors, telework performed outside of working hours and part-time work. Also, family situation and having small children at home reduce time use control, according to the paper.

Other studies focus on the mentality of teleworkers (Toniolo-Barrios and Pitt, 2020; Radulescu et al., 2021). Radulescu et al. (2021) searched for the impact of the COVID-19 pandemic on the Romanian labour market using a survey on 548 people. According to their analysis, the respondents obtained better results and maintained a similar income, but the pandemic influenced the mentality of the employees, with a focus on safety conditions and complex health insurance. Moreover, the authors obtained that the pandemic induced an increase of unemployment in Romania.

3 Research methodology and data

In order to assess the impact and perspectives of teleworking both on employees and employers, we collected data based on two volunteer online surveys, during February 19th and 4 March 2021. Similar methods have also been used in the literaturę (Dima et al., 2019; Thulin et al., 2019; Belzunegui-Eraso and Erro-Garces, 2020; Davidescu et al., 2020; Lopez-Igual and Rodriguez-Modrono, 2020; National Institute of Administration, 2020; European Economic and Social Committee, 2021; Radulescu et al., 2021). We opted for this method as it is an efficient method, it does not involve high costs (such as sending people, who are trained to explain the survey, to the field) and it is not dependent on the geographical position of the authors (given the fact that the survey is sent online).

The surveys are presented in Annex one and Annex 2, at the end of the article. The main objective is to identify the position of Romanian employees and employers/managers on teleworking, to diagnose the real situation of teleworking alongside the pandemic. Plus, we want to assess how the Romanian employees and employers relate to the advantages and disadvantages of teleworking and what is the willingness to continue the telework activity and in the aftermath of the pandemic.

The sample addressed to the employees on execution positions is composed of 400 respondents, while the sample regarding the employers and management positions consists of 121 respondents. The survey encompasses closed questions with a single answer option or multiple options using the Likert 5-trep scale as used in Dima et al. (2019) and Davidescu et al. (2020). The results for horizontal analysis are presented as absolute frequencies, relative frequencies and weighted averages for items measured with the Likert scale and have been obtained by using SPSS 23.0 Statistical Package for Social Sciences.

For all the questions we have obtained the *p*-value lower than 0.001, which leads to the conclusion of normal distribution for respondents with execution positions. We have tested for the normality of the answers' distribution using the Kolmogorv—Smirnov methodology, which is based on the comparison of the cumulative proportions of the observed and theoretical frequency distribution derived from H0 (Pupion and Pupion, 1998):

$$D_t = 1.36 * \sqrt{\frac{n_1 + n_2}{n_1 * n_2}}$$

n1, n2 being the volume of the two compared samples. As we considered that the significance level α equals 0.05, according to the methodology, the resulted value of the variable t is 1.36. For data collected using the 5-step Likert scale, we have tested the reliability of the scale using Cronbach 'Alpha coefficient (Goforth, 2015):

$$\alpha = \frac{N * \bar{c}}{\bar{v} + (N - 1) * \bar{c}}$$

where, α = Cronbach 'Alpha coefficient; N = number of scale items; $\bar{c}$ = average of all covariances used between items; $\bar{v}$ = average variance of each item.

The values obtained for this coefficient differ between and across the two surveys, depending on the questions. For instance, in the case of the executive functions survey, all values obtained are above or approximately equal to 0.7, which indicates a good reliability of the statistical scale, while in the case of the survey regarding the management positions, the Cronbach 'Alpha

coefficient is above 0.7 for items that measure personal advantages and disadvantages (0.863 and 0.824 respectively) and those perceived for the organization (0.702 respectively 0.936). For the other items, the coefficient is below the accepted level of 0.7.

We have applied Oneway ANOVA (as in Davidescu et al., 2020) in order to analyse the existence of significant differences between the average scores recorded by items measured with the Likert scale (positioning against telework, perception of telework efficiency, personally perceived advantages and disadvantages, advantages and disadvantages for the organization). We only present the results for which the *p*-value is lower than 0.05. ANOVA examines the differences between the average values of the dependent variable (scores given to statements measured with the Likert scale) under the effect of independent variables, such as the type of organization in which they work or hold management positions (Malhorta, 2004). The independent variable is usually qualitative and the null hypothesis H0 refers to the equality of the average scores (Ostertagova and Ostertag, 2013) of the categories of respondents holding an execution/management position depending on the type of institution/organization or its size.

We have also applied the nonparametric Mann - Whitney *U* test in order to analyse whether there are statistically significant differences between the items measured by the Likert scale for women and men. We only present the results for which the *p*-value is less than 0.05. The test has been also used as a bidimensional analysis of a nominal-ordinal pair of variables and is determined as follows (Nachar, 2008):

$$Z_U = \frac{Ucalc - \frac{n_1 * n_2}{2}}{\sqrt{\frac{n_1 * n_2 (n_1 + n_2 + 1)}{12}}}$$

where n1 and n2 represent the sizes of the two independent samples. The Mann - Whitney *U* test is applied when in the study there are ordinal variables on a variable coming from two independent samples (in our case men/women) and there is scope for verifying the existence of a difference between these two groups (Lambin et al., 1990).

In order to analyse the degree of association/correlation between the Likert scale items related to the positioning of respondents to telework and the perception of the efficiency of this activity, both for respondents with executive and management positions, we have applied Pearson parametric correlations (Brooks, 2008):

$$\rho_{x,y} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

where: n is the sample size, x and y represent the individual values of the two variables.

As for the structure and characteristics of the two surveys, one is based on the perceptions of employees holding executive positions and the other is based on the perception of managers regarding teleworking, in order to assess its impact both on employees, but also on firms' efficiency.

Most respondents with executive positions are employed in private institutions or companies (55.5%) with over 250 employees (61.5%), the average age is about 40 years, and the average monthly net income about $ 1,360, more than two-thirds of the respondents being women. A large proportion of the managers (86%) come from private companies, with a high share of those with less than 50 employees (77%), the proportion of women/men is approximately equal, the average age is 45 years old, and monthly net average income is $ 1,509. (Table 1).

4 Empirical results

The results obtained on the basis of the two surveys reveal that 48% of the executive staff performed telework permanently in the context of the pandemic, compared to 22.3% of the managers. On the other hand, 37.2% of the respondents with management positions benefited from a hybrid scheme combining telework and physical presence at the workplace (compared to 34.5% among executive staff), and 30.6% performed telework occasionally (compared to 14.5% among executive staff), the remaining 9.9% of respondents with management positions stating that they did not practice telework at all (compared to 6% of respondents with executive positions).

Prior to the COVID-19 crisis, only 36.5% of the executive staff performed telework occasionally, while among the management staff, 6.6% performed telework on a permanent basis, 37.2% occasionally and more than half (56.2%) never. There has been, therefore, a significant increase in teleworking in the context of the pandemic, which is more pronounced in terms of executive functions.

Teleworking is seen by both management and executive staff as a good option, stating that work can be carried out efficiently both at the workplace and at home. The options related to total disagreement (I totally dislike it) and the existence of disruptive factors in teleworking conditions have registered quite low scores (Table 2).

The attitude of the respondents regarding their efficiency while performing teleworking is similar for the two categories, both for managers and executive staff being marked approximately neutral scores. Thus, an important part of the respondents consider that they have a higher efficiency or are equally efficient when practicing teleworking, compared to the situation in which they are physically present at the workplace.

During teleworking, the main ways of interaction, for both samples, were: email, phone calls, instant messaging applications and dedicated meeting platforms (Zoom, Google, *etc.*). A very small part of the respondents claim that they did not use these communication channels.

TABLE 1 The structure of the two samples.

Socio demographic variable	Executive positions n = 400		Management positions n = 121	
	Absolute frequency	Relative frequency	Absolute frequency	Relative frequency
Gender				
Males	124	31%	56	46.3%
Females	276	69%	65	53.7%
Age				
Less than 25	32	8%	2	1.7%
26–40	264	66%	51	42.1%
41–55	86	21.5%	43	35.5%
Over 55	18	4.5%	25	20.7%
Net monthly wage				
Minimum wage	12	3%	-	-
$321 - $619	26	6.5%	-	-
$620 - $1,236	144	36%	42	34.7%
$1,237 - $1857	142	35.5%	51	42.1%
$1857 - $2472	54	13.5%	21	17.4%
Over $2472	22	5.5%	7	5.8%
Type of institution				
Public	124	31%	12	9.9%
Private	222	55.5%	104	86%
Educational (public)	54	13.5%	5	4.1%
Size of the institution				
Less than 10 employees	28	7%	52	43%
11–50 employees	56	14%	41	33.9%
51–250 employees	70	17.5%	19	15.7%
Over 250 employees	246	61.5%	9	7.4%

TABLE 2 Positions regarding teleworking (medium scores).

	Executive positions	Management positions
For me it is a perfect option	3.71	3.57
I am able to work efficiently both when teleworking and at the workplace	3.76	3.69
I totally dislike it	1.9	2.09
When teleworking, I consider myself to be less efficient, due to the distractions like family/children	2.38	2.61

For executive staff, professional communication with colleagues/superiors/subordinates/partners/clients during telework periods was slightly affected, as follows: for 10% - largely (8.3% among management staff), 26.5% - moderate (20.7% among management staff), 31.5% - to a small extent (similar weight for both samples), 32% - not at all (39.7% among management staff).

For executive staff, the aspects regarding expenses affecting the personal budget in order to create at home a proper working environment, reveal that 47% of the respondents have made such expenditures, 38.5% have stated that they had all the necessary means for teleworking, and only for 14.5% the employer provided all the necessary means.

TABLE 3 Advantages of teleworking (medium scores).

	Executive staff	Management staff
Saving the time spent in traffic	4.35	4.22
Work schedule flexibility and better schedule management	4.05	4.09
Saving money (for food, fuels, clothes, shoes, and so on)	3.67	3.86
Better management of the balance between private and professional life balance	3.53	3.32
Better supervision of children	3.35	3.31
Lower stress due to better time management: punctuality (related to time no longer spent in traffic)	3.49	3.9
Work efficiency (I work better when I'm alone than surrounded by colleagues at the office)	3.29	-
Development of digital skills	3.37	-

TABLE 4 Individual disadvantages related to teleworking (medium scores).

	Executive positions	Management positions
Reduced socialization	3.57	3.76
Existence of disruptive factors (noise, family tasks)	2.9	2.91
Difficulties in coordinating with other team members	2.79	2.86
The way of monitoring telework does not allow for an adequate reflection of the complexity/volume of the performed activities	2.96	2.94
Distorted perception regarding the professional efficiency during teleworking of the superiors/colleagues who do not practice teleworking	2.81	-
Lack of procedures regarding teleworking	2.68	2.85
Lack of an electronic signature	-	2.69

Most employees spent on furniture (118), consumables (paper, toner, etc.- 90), computer/laptop/printer (78), ensuring ergonomic comfort at home - 162, the average amount spent being about 1,300 lei. The structure of the amounts spent is as follows: under $25–14.5%, $25 - $124: 19%, $124 - $ 248: 12%, $248 - $1,238: 18.5% and over $1,238 - only 2.5%.

With regard to overtime during teleworking periods, the structure of the responses is somewhat similar for the two samples: 16.5% of executive staff answered "yes, to a large extent" (compared to 11.6% of the management staff), 32% - moderate (36.4% of managers), 6% - to a very small extent (25.6% of managers) and 25.5% never (25.6% of management). Regarding the advantages related to telework, the respondents from both samples consider that saving the time spent in traffic and flexibility of the work schedule are the most important advantages, but the other advantages also registered high scores. In the case of executive staff, the efficiency of the activity and the development of digital skills are also noted (Table 3). In contrast, the biggest disadvantages perceived in both surveys relate to reduced socialization (Table 4).

Instead, the biggest disadvantages perceived in both samples refer to the low degree of socialization.

An important conclusion of our research is that teleworking is beneficial to the profitability/efficiency of the organization, according to the answers provided by management staff, and this idea is reinforced by the relatively low scores obtained in the case of the options related to a negative impact of telework on the organization's activity or employees' lower efficiency (2.45 and 2.53, respectively).

The respondents holding management positions show a somewhat neutral opinion (sometimes disagreeing) on the advantages and disadvantages highlighted by the situation so far. One possible explanation is that the benefits are likely to be visible over a longer period of time (Table 5).

About half (49.8%) of the respondents holding management positions claim that the organizations in which they operate have provided funds to employees for the purchase of goods needed in telework, the structure of destinations being as follows: consumables - 34%, payment of part of utilities - 12%, office furniture - 19% and 36% for the purchase of a computer/laptop.

Out of the 121 respondents holding management positions, almost one-third (30.6%) will offer employees the opportunity to choose between telework and physical presence at the workplace, 28.1% only when appropriate, 19% consider it not to be a good option, 14.9% stated that the final decision does not belong to

TABLE 5 Advantages and disadvantages for the organization.

Advantages		Disadvantages	
Lower salary costs	2.13	Lower efficiency ofthe entire company/institution	2.4
Lower operating costs (utilities, rents, etc.)	2.88	Lower efficiency of some employees	2.46
Improved organization	2.66	Difficult communication	2.5

them and only 7.4% will offer this possibility only where teleworking is suitable. The results we obtained confirm, therefore, the idea circulated in other papers, according to which teleworking replaces the physical presence at work, and its significant practice will be maintained even after the pandemic.

We complemented our research with a vertical analysis of the two surveys. Thus, we applied Oneway ANOVA in order to test the existence of statistically significant differences (p-value <0.05) between the average scores given in the case of the statements from the items measured with the Likert scale. We obtained statistically significant results for the executive staff depending on the type of institution in which they operate and in the case of the management staff depending on the size of the organization. We have chosen the size of the organization considering the fact that, according to the survey structure, 86% of the management respondents come from an institution/company with private capital.

Thus, we have found differences of opinion and perception regarding the positioning about telework ("It is a perfect option for me" and "I totally dislike"), in the case of respondents employed in public education institutions (3.15 and 2.33), on the one hand, those employed in public institutions (3.74 and 1.92) and those employed in companies with private capital (3.83 and 1.77), on the other hand. The same grouping of different perceptions is maintained from the perspective of telework efficiency, respectively between employees in public educational institutions (2.70), on the one hand, and those employed in public institutions (3.34) and or in private companies (3.11), on the other hand.

Regarding the personal advantages felt in the context of teleworking, only for one of the eight stated advantages there were significant differences, so that although the respondents from public institutions (3.56) and those from private companies (3.64) agree that they managed more effectively the balance between private and professional life, public education employees have a neutral opinion on this issue.

There are also different opinions regarding the following disadvantages of teleworking: the distorted perception of the efficiency of teleworking by superiors/colleagues who do not practice teleworking, on the one hand, and the lack of procedures for telework, on the other.

Within the survey for management positions, opinions and perceptions have registered statistically significant differences in the case of perceived efficiency in telework, respectively of the opinion: "It depends on the situation, sometimes more efficient, sometimes less efficient". Respondents agree with this statement (with a score of 3.89) in organizations with more than 250 employees, as opposed to organizations with less than 250 employees, that register an overall neutral-positive opinion (from 3.1 to 3.43).

The statement "Distorted perception of the efficiency of professional work through telework by superiors/colleagues who did not work telework" registers a neutral - positive score (3.17) in micro organizations (less than 10 employees) and a slight disagreement (between 2.56–2.68) in all other cases.

In addition, the statement "Employees you have subordinated were less efficient in professional activities carried out through telework, if they were physically present at work" led to the grouping of respondents' opinions as follows: those in organizations with 11–50 employees disagreed with this statement, while all the others were neutral. It can therefore be concluded that teleworking does not affect the efficiency of employees, but most likely this depends on the organization of the entity.

According to managers, one of the disadvantages of teleworking for the organization, respectively lower efficiency of the entire company/institution, grouped the opinions as follows: managers in organizations with 51–250 employees were neutral while all the others disagreed. For the other disadvantage (difficult communication), the opinion of those in organizations with 51–250 employees differs from the others' (neutral for the first group vs disagreement for all the others). Therefore, we can conclude that, in general, telework does not affect the efficiency of companies or communication in a professional sense.

However, the results obtained by running Oneway ANOVA indicate that, for these items there were large, statistically significant variations (differences of opinion) around the average score both within each group (type of organization in the case of execution positions, respectively size organization in the case of management positions), as well as between groups.

We used the nonparametric Mann - Whitney U test in order to analyse the statistically significant differences between the positioning of men and women regarding teleworking, its efficiency, advantages and disadvantages, both in the case of executive functions (Table 6) and in the case of positions management (Table 7).

TABLE 6 Results of the Mann—Whitney U for executive positions.

	Mann-whitney U	Wilcoxon W	Z	Asymp. Sig. (2-Tailed)
Positioning about teleworking				
During teleworking I am distracted and consider myself less efficient, due to the fact that I live with children/family	3,241.000	12,832.000	-2.830	0.005
Perceived efficiency in the context of telework				
Generally, less effective compared to when physically present at the workplace	3,497.500	13,088.500	-2.129	0.033
Perceived disadvantages in the context of telework				
Reduced socialization	3,548.000	13,139.000	-1.995	0.046
The way of monitoring telework does not allow for an adequate reflection of the complexity/volume of the performed activities	3,569.500	13,160.500	-1.931	0.050
Lack of procedures regarding teleworking	3,384.500	12,975.500	-2.452	0.014

TABLE 7 Results of the Mann—Whitney *U* test for management positions.

	Mann-whitney U	Wilcoxon W	Z	Asymp. Sig. (2-Tailed)
Positioning about teleworking				
It is a perfect option for me	1,399.000	3,544.000	-2.269	0.023
I am able to work efficiently both when teleworking and at the workplace	1,353.500	3,498.500	-2.563	0.010
Disadvantages regarding teleworking				
Lack of procedures regarding teleworking	1,456.000	3,601.000	-1.973	0.048
Advantages for the organization due to teleworking				
Lower operating costs (utilities, rents, *etc.*)	1,327.500	3,472.500	-2.638	0.008
Disadvantages regarding teleworking for the organization				
Lower efficiency for the entire company/organisation	1,394.500	2990.500	-2.291	0.022
Difficult communication	1,482.000	3,078.000	-1.814	0.050

The results show that women have a different perception than men regarding the lower efficiency in the context of telework while living with family and/or children, compared to the physical presence at the workplace: men have a neutral position (2.71 and 2.68), while women disagree (2.22 and 2.32). Therefore, the results obtained indicate that women have the ability to optimize their work and administrative activities related to family/children, in line with the results obtained in the literature.

Regarding the disadvantages of teleworking, men agreed with reduced socialization, while women had a neutral opinion. Also, women did not perceive as a disadvantage of teleworking the lack of procedures, while men did.

The different opinions depending on the gender of the respondents holding a leadership position are presented in Table 7.

The positioning regarding telework is perceived differently depending on the gender of the respondents. Men holding management positions agree that teleworking is a perfect option (3.82), while women position themselves somewhat neutral (3.35). The same differentiation between opinions (men agree, women are neutral) was registered for the statement "I can carry out my work efficiently both while teleworking and at the workplace".

Statistically significant differences were also registered in the case of the lack of procedures for teleworking, men adopting a neutral position, while women disagreeing. At the same time, men agreed on the advantage of lower costs for the organization due to teleworking, while women were neutral. The results indicate that men disagree, and women are neutral in terms of lower efficiency for the entire company/institution and also in the case of difficult communication.

We also evaluated the degree of association between the items related to the respondents' positioning towards telework and the perception of its efficiency using the Pearson parametric correlation, both in the case of execution functions (Table 8) and in the case of management positions (Table 9).

The results obtained in the case of the executive staff indicate the existence of either direct (+) or inverse (-), low intensity (0.208–0.344) or moderate (0.458–0.546) correlations.

TABLE 8 Pearson correlation coefficients for execution functions.

	Generally, more effective than when physically present at the workplace	Generally, less effective than when physically present at the workplace	Always equally effective	It depends, sometimes more efficient, other times less efficient
It's a perfect choice for me	0.344	-0.465	0.458	-0.055
I can carry out my work efficiently both while teleworking and at the workplace	0.307	-0.343	0.339	-0.003
I totally dislike it	-0.302	0.539	-0.253	0.223
During teleworking I am distracted and consider myself less efficient, due to the fact that I live with children/family	-0.208	0.546	-0.247	0.273

TABLE 9 Pearson correlation coefficients for management positions.

	Generally, more effective than when physically present at the workplace	Generally, less effective than when physically present at the workplace	Always equally effective	It depends, sometimes more efficient, other times less efficient
It's a perfect choice for me	0.623	-0.617	0.488	-0.167
I can carry out my work efficiently both while teleworking and at the workplace	0.590	-0.454	0.493	-0.013
I totally dislike it	-0.421	0.487	-0.339	0.195
During teleworking I am distracted and consider myself less efficient, due to the fact that I live with children/family	-0.457	0.479	-0.561	0.058

By analysing the direction and intensity of correlations between items that measure the position of managers regarding teleworking and the perception of their efficiency (Table 9), we can see that they have the same direction as those obtained for the executive functions, but the correlations are of medium to moderate intensity, as the values of the coefficients are higher than those obtained for executive functions. The results indicate the existence of both direct (+), and also inverse (-) correlations, of medium/moderate to strong intensity (0.421–0.623).

5 Discussion

In the context of the restrictions imposed by the COVID-19 crisis, our research reveals a significant increase in the practice of teleworking, more accentuated for executive positions, compared to management ones.

According to the results we have obtained, the efficiency with which people carry out their professional activity through telework is similar or even higher, compared to the situation in which they are physically present at the workplace. Similar results have been obtained by Calmels et al. (2021), Davidescu et al. (2020), National Institute of Administration (2020) and Radulescu et al. (2021).

We can conclude, therefore, that teleworking has become, at least for some sectors, a determining factor of productivity growth, and this evolution will continue and will be amplified, most likely, through digitalization.

According to the respondents, teleworking has many advantages, both for management and executive functions, most important being the time saved by avoiding traffic and also making the work schedule more flexible, that indicates a new paradigm in time management and significant effects in terms of social relations. Respondents also significantly appreciate the fact that, in the context of teleworking, they saved significant amounts of money, managed the work-life balance more effectively, eliminated the stress of punctuality and even had the opportunity to supervise their children more closely. Similar results have been obtained by Dima et al. (2019), Calmels et al. (2021), Davidescu et al. (2020), Tremblay and Thomsin (2012), Lopes et al. (2014). In the case of the executive staff, it is also noted a higher efficiency of the activity, in the conditions of a quieter work environment, but also the development of increased digital skills. However, Vasilescu (2021) highlighted the fact that

almost half of the houses in Romania are overcrowded and this might be a disadvantage when working from home. The idea of intensified time pressure when teleworking within an overcrowded house is also supported by Thulin et al. (2019).

Beyond the benefits above reported by individuals, according to managers, telework is beneficial to the profitability/efficiency of the organization, as they, in general, disagree on the negative impact of telework on the organization's activity or lower employee efficiency while teleworking.

Thus, most managers agree to offer employees the opportunity to choose between teleworking and physical presence at work, in general, when appropriate, or where teleworking is favorable, while less than one-fifth believe that teleworking is not a good option. Therefore, a flexible scheme that combines teleworking with physical presence at the workplace would be a suitable option for the future, in order to find a balance between streamlining the activity of organizations, on the one hand, and optimizing the professional/personal activities of employees, on the other hand. The mix idea is also supported by Davidescu et al. (2020) and National Institute of Administration (2020).

An important aspect obtained from our research refers to the fact that there are differences of opinion at the level of staff working in public education institutions, compared to the other respondents. In general, they do not feel comfortable with the telework option and are generally of the opinion that their efficiency is lower than in the conditions of physical presence, which indicates that teleworking is still being improved in relation to the efficiency of the teaching-learning process, this situation being different from other types of activities. For example, Raišiene et al. (2021) obtained a similar result in their study, but Catană et al. (2021) obtained that teachers state that blended learning (mixed system) is the best way, while students and auxiliary and non-teaching staff consider that the traditional system (face-to-face) represents the best way to carry out the educational process.

In fact, education employees have a neutral opinion about the fact that, in the context of telework, they had the opportunity to manage more effectively the balance between private and professional life, while other respondents fully confirmed this idea. Such a conclusion seems to confirm the inertial and gradual character by which the great public systems assimilate the challenges of digitalization, given the low degree of technological and digital endowment in the Romanian education system. The use of teleworking methods in education is likely to become one of the strongest challenges of the XXI century, especially in the university education, whose profile favors distance learning much better.

Prior to the COVID-19 crisis, Romania had an extremely low share of teleworkers compared to EU countries, most likely for reasons related to the structure of the economy (lower value-added sectors, lower share of services and high share of agriculture), the lack of regulations on telework and probably the lack of large-scale digital skills. For example, in 2019, less than a third (31%) of Romania's population reported basic or advanced digital skills, one of the lowest shares in Europe, while the EU average was 56%. As mentioned above, our study reveals an intensification of employees' digital skills due to telework, as a result of the restrictions imposed by the sanitary crisis.

Given the positioning of individuals holding both management and executive positions, regarding the efficiency of teleworking, as well as in relation to advantages and disadvantages, we believe that, among other changes that will take place at the economic and social level, the COVID-19 crisis could train a paradigm shift regarding the practice of telework in Romania, in the sense that it will be used more intensively and will be a way to streamline business in various economic sectors that are characterized by high added value (such as business development services, IT services, consulting, *etc.*), alongside with an improvement of the balance of personal/professional life. Labor efficiency is a delicate topic within the European Union, as it is considered that the EU promotes income growth in areas that account for low labor efficiency, which leads to moral hazard effects on the efficiency of firms (Jianu et al., 2021).

Thus, it is expected that these changes will increase the share of these branches in total national production, as Romania has a potential for development in these sectors. In fact, in 2020, despite the pandemic context, some of these sectors recorded increases that were likely to have a positive impact on both macroeconomic developments and the current account balance. For example, in 2020, Romania registered an increase in current account surpluses for IT services (by 5.8%) and business services (by 61%).

Given the financial instruments offered by the European Commission in the context of the pandemic, Romania benefits from consistent support for economic recovery, the transition to a green, digital economy and achieving a high degree of resilience. The significant financing Romania can benefit from in this context represents a huge opportunity in the sense of modernizing and developing the economy, by streamlining activities, by stimulating high-tech sectors which produce high added value, by accelerating the digitization process, both in the private and especially in the public sector. However, it must be noted that some authors found that the efficiency of the employees in the public sector during teleworking is questioned, due to the negative perception of the public regarding public servants and also by the limited trust that public institutions manage properly their digital procedures (Vasilescu, 2021).

6 Conclusion

We conclude that the Covid-19 pandemic will lead to a paradigm change in the sense of accelerating the use of teleworking, which will contribute to growing labor productivity, enhancing firms' efficiency and profitability, while having several advantages both for employers and

employees, and thus contributing to life improvements for the people involved.

In all the respects described in our paper, teleworking can have a significant beneficial impact: it determines the productivity growth and the streamline of the companies' activity, accelerating the digitization process, and, last but not least, it can contribute to reduce carbon dioxide emissions, by reducing territorial mobility, especially in urban areas, where pollution is one of the major problems. In fact, the biggest advantage of teleworking perceived by respondents in our study refers to the reduction of time spent in traffic, which is equivalent to a reduction in pollution.

However, beyond the social and environmental consequences, teleworking is asserted mainly by its economic motivations, by increasing productivity and overall efficiency of activity in public and private organizations, that opens new technological and institutional challenges in terms of digitalization and regulation in the legislative plan.

An important limitation of our study regarded the difficulty of obtaining a consistent number of answers, which depended on the willingness of employees and managers to respond to the survey. That is why we opted for an anonymous survey easy and fast to fill out.

A future research direction would consist in resending the survey when the pandemic is over and making a comparison between results obtained in 2021 and those that would be obtained in the future. Also, it would be interesting to assess the results obtained for this survey in other countries (similar developing countries in the region or developed EU Member States) and make comparisons between the results.

However, given also the issues presented in other papers (Vasilescu, 2021), maybe the most interesting future direction for research regarding teleworking in Romania would refer to testing the theory according to which teleworking in local public administration is quite a challenge.

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.

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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Do ESG scores have incremental information value on the primary bond market?——evidence from China

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ESG scores are essential information tools in the capital market, but prior study has not fully discussed the effect and internal mechanism of ESG scores on bond investors' risk pricing in the primary market. The purpose of this study is to investigate the relationship between the ESG scores and risk premium of bond issuance based on the sample of Chinese listed corporations. We find that when ESG scores of the bond issuer are higher, the investors will require a lower risk premium. The result indicates that ESG scores already have positive information effect in Chinese primary bond market. Furthermore, we make mechanism and heterogeneity tests to prove that ESG scores can provide investors with incremental information, which is helpful for bond investors to identify risks and price effectively. Our study in the context of the emerging economy of China examines the incremental information value of ESG scores for bond investors, and provides evidence for the application of sustainable development concepts in global capital markets.

KEYWORDS

ESG scores, bond risk premium, sustainable business performance, debt financing capacity, incremental information

1 Introduction

ESG scores, as very important and increasingly concerned principles, have been integrated into all levels of the portfolio allocation process and regarded as a new dimension to redefine bond investment. Previous studies have paid attention to how ESG scores play an information decision-making effect in the secondary circulation market of bonds (Immel et al., 2021; Kanamura, 2021). Actually, for the primary bond issuance market, the basic information of the corporate quality will be more valued by investors, especially the ESG scores that reflects the long-term investment value of the corporation. It is an essential criterion for measuring whether a corporation has enough social responsibility (Hong, 2019) and sustainable business performance (Baker et al., 2021). Therefore, when the corporation has a higher ESG score, it will send a positive

signal to investors in the primary bond market, which will alleviate the information asymmetry and reduce the risk premium demanded by investors.

But there has been little discussion about the influence of ESG scores on risk premium in the primary bond issuance market. Especially under the influence of current COVID-19, the concept of sustainable development related to ESG has further become the focus of attention; In addition, as an emerging economy, China already has the world's second largest bond market. In this context, the purpose of this study is to explore the influence of ESG scores on the risk premium of bond issuance in Chinese market, which will help to understand the extent to which the concept of sustainable development is applied in the global capital market.

Based on information asymmetry theory, we used ESG scores, bond and financial data of corporations which listed on the Shanghai and Shenzhen Stock Exchanges over the period 2016 to 2020, and the pooled regression to study the relationship between the ESG scores and risk premium of bond issuance. Results indicate that ESG scores which are higher, will contribute to significantly lowering the risk premium of issuing bonds, which indicates that ESG scores exert a positive information effect in the Chinese primary bond market. Meanwhile, we used a two-stage least-squares methodology to alleviate the endogeneity problems. Additionally, through the mechanism test and further analysis, we proved that ESG scores can provide investors with incremental information value, which is helpful for bond investors to identify risks and price effectively.

Our study makes several important contributions to the literature and fills the research gap. First, it extends the research on the information effect of ESG scores in capital market. Previous studies tended to focus on the impact of ESG scores on portfolio returns in the stock market, but few studies investigated the information effect of ESG scores in the primary bond issuance market. Second, this paper enriches the researches on the influencing factors of bond issuance cost. There were many literatures that discussed the factors affecting the cost of corporate bond issuance, but few literatures focused on ESG scores issued by financial institutions. Third, this paper contributes to enriching the relevant literature on discussing the incremental information value of ESG scores. Previous literature mainly focused on the stock market, but the primary bond market as an investment and bond issuance market, the basic characteristics and behavior of the bond issuing corporations are crucial to investors, such as ESG scores. Therefore, exploring the impact of ESG scores on China's primary bond market will help to expand the literature on discussing the incremental information value of ESG scores.

The main potential implication of this paper is to provide strong evidence for the application of the concept of green sustainable development in the global capital market. Unlike other economies, China is an emerging economy with the world's second-largest bond market, but its capital market is less efficient. In such market, market information cannot be efficiently used as an investment tool, but we have obtained very significant results, indicating that ESG concept has been fully applied in the global capital market.

This paper proceeds as follows. We mainly review related literature on the effect of ESG scores in Section 2. We present the theoretical development and hypothesis in Section 3. And then, we provide the research design in Section 4. Further, we discuss the empirical results in Section 5. We thoroughly examine the incremental information effect of ESG scores from two directions in Section 6. We further explore the heterogeneity of the information effect of ESG scores in Section 7. In Section 8, we conclude.

2 Literature review

ESG scores will not only have a significant influence on the corporate financial policy, governance and performance (Aboud and Diab, 2019; Hong, 2019) but also have a significant information effect on the capital market (Baker et al., 2021). First of all, an important component of the information effect study of ESG scores is the impact on investor decisions and earnings in the stock market. As an effective value decision-making tool, ESG concept is widely applied in the practice of stock portfolios, but the results reached by scholars through current study are inconsistent. On the one hand, the market believes that higher ESG scores will have an active influence on the investment portfolio (Czerwińska and Kaźmierkiewicz, 2015). Erragragui and Revelli (2016) found that ESG screening on the stocks that comply with Islamic law has no adverse impact on the stock return, and the portfolio with a good ESG score has better stock performance. Similarly, based on the study of Deng and Cheng (2019), we can conclude that the relationship between ESG indicators and stock market performance was positive. Stotz (2021) found that stocks with higher ESG scores have lower discount rates. In addition, Engelhardt et al. (2021) tested the correlation between ESG scores and stock performance during the COVID-19 pandemic and found that high ESG scores were associated not only with higher abnormal returns but also with lower stock price fluctuations. On the other hand, it is not necessarily for higher ESG scores to exert significant additional value to stock investors. Auer and Schuhmacher (2016) concluded that actively screening stocks with high or low ESG scores cannot provide better risk adjustment performance than a passive investment in the stock market.

Secondly, in recent years, the study issue pertaining to the influence of ESG scores on bond investors has just gotten attention, and the related research scenarios mainly focus on the secondary bond market. In the early stage, Hachenberg and Schiereck (2018) report that the influence of the ESG scores on

bond pricing is significant. Subsequently, Badía et al. (2019) found that in terms of the ESG dimension, the performance of government bonds with high scores is better than that of government bonds with low scores at any social responsible investment demand levels. Li et al. (2020) found that ESG scores are closely related to the default probability of corporate bonds. With the deepening of study, scholars began to attach more importance to the studies of internal mechanism of ESG score information effect on the bond market. Research by Bahra and Thukral (2020) has found that ESG scores can boost the result of the portfolio by reducing withdrawal rate, reducing portfolio volatility, and even slightly increasing risk-adjusted return at times. When analyzing the relationship between ESG score and bond return, Jang et al. (2020) also believed that ESG score is an effective supplement to credit rating. In particular, information related to a firm's downside risk is included in the ESG score, which is specifically significant for understanding small corporations and other corporations with a high degree of information asymmetry. Recently, Kanamura (2021) found that during COVID-19, ESG components have hedging effects on the downward risk of bond prices.

The research about the impact of ESG scores on bond investors in the capital market is in its infancy. ESG score information is also effective incremental information of the capital market, and the prior study has been focusing on the capital market response and other related research. But it is more biased toward the investment portfolio income of the stock market, and in recent years, the research on the bond market had little discussion still. At the same time, few studies investigated the information effect of ESG scores in the primary bond financing market, especially in China, as an emerging economy, the relevant researches are scarce. However, the Chinese bond financing market has developed rapidly. It has become the second largest bond market worldwide, which serves the Chinese economy and attracts investors from all over the world to allocate assets. Especially in recent years, corporate bond defaults have entered a tumultuous period. The quality of issuing corporation development has become a core issue that the market pays attention to, and traditional financial information cannot fully reflect the problems or potential risks in corporate development. Therefore, on the basis of the influence of ESG scores on the risk perception and decision-making of investors in the Chinese primary financing market, our study will have important practical significance and theoretical value.

3 Theoretical development and hypotheses

ESG scores are comprehensive assessment of corporate ESG performance published by financial institutions in the capital market, and it has become an important source of information for investors to make value investments.

On the one hand, ESG scores provided investors with complete risk information (Zopounidis et al., 2020; Yang et al., 2021). ESG scores as critical non-financial information can not only reflect the importance the company attaches to environmental performance, social responsibility and corporate governance in the development process, but also reflect the practical development level of the three aspects. As the ESG criterion is accepted gradually in China, investors attach more importance to corporate ESG behavior and performance. However, it is in its infancy for Chinese corporations to disclose ESG information (Ruan and Liu, 2021). According to statistics, as of mid-2021, 1092 A-share listed corporations have disclosed ESG reports for 2020, accounting for only 25.3% of the total. Due to the small number of disclosed ESG reports and the lack of supervision, the disclosure indicators of ESG report is not uniform, as well as lower comparability and completeness. There is a large gap in investors' demand for ESG information.

However, unlike ESG behavior information disclosed by the corporation itself, ESG scores are market index evaluated by financial institutions after integrating non-public and public information, so the ESG information provided is more complete. Furthermore, financial institutions obtain ESG related information through multiple channels, such as public and non-public methods (ESG report, research and interview). Meanwhile, the financial institution needs to comprehensively consider the incremental information such as ESG risk exposure, management level and ESG performance to reflect sustainable development potential and the ability to deal with ESG risks of the corporation. MSCI believes that applying ESG scores to investors' investment decision-making process can help investors capture some risks and opportunities which may not be identified in the traditional financial analysis, thereby helping investors reduce investment risks and improve long-term investment returns. In addition, ESG scores of financial institutions are not just a simple integration of corporate ESG information, but also its quantitative analysis process. This information is expressed in qualitative to quantitative data, which is more helpful for investors to compare and analyze corporations. Therefore, for investors, the information provided by financial institutions on ESG scores has an incremental effect.

On the other hand, practice and prior study show that higher ESG scores help to reduce corporate risk (Zhang et al., 2021), and reduce future development risk perceived by investors. From the corporate perspective, a higher ESG score helps companies to increase environmental, social and governance attention, and help to optimize internal governance procedures and mechanisms and attract more high-quality employees. According to the current ESG performance, the corporation can adjust daily financial and operating policies to reduce ESG risk. From an external environmental perspective, a higher ESG score means that the corporation has more

investment in ESG performance (Jang et al., 2020) and lower risk (La Torre et al., 2020), which will lead to the attention and supervision of analysts, media and investors. These effects of the ESG scores will further encourage corporation to restrain their risky behavior. (Brounen et al., 2021). Under the background of emission peak and carbon neutrality, corporations with high ESG scores will receive preferential policy support from the government and pay more attention to the ability of sustainable growth. Therefore, higher ESG scores help to promote the steady and benign development of the corporation, and then decrease the expected risk perceived by investors.

In summary, Higher ESG scores not only provide investors with incremental information on current corporate risk, but also help to reduce investors' expectations of corporate future development risks, thereby reducing information asymmetry. In practice, ESG scores have been integrated into the process of portfolio allocation in the bond market. ESG scores are becoming a new dimension to redefine bond investment. However, prior study has mainly focused on the secondary bond trading market (Bahra and Thukral, 2020; Kanamura, 2021), and there has been little discussion about the information effect in the primary (issuance) market. In depth, investors of the secondary bond trading market will be affected by market factors, such as liquidity. The primary bond market is not only an investment market, but also a bond financing market for corporations. Investors attach more importance to the basic characteristics and behavior of bond-issuing corporations. Higher ESG scores will help to send a positive signal to investors in the bond financing market, and then reduce the risk premium demanded by investors. Based on the relevant theoretical analysis mentioned above, the following hypothesis are proposed:

Hypothesis. When ESG scores of the bond issuer are higher, the investors will require a lower risk premium.

4 Research design

4.1 Sample selection and data sources

To investigate the hypothesis, we selected the sample as follows:

First, we retrieved ESG scores information from the Wind database which provides ESG scores of SynTao Green Finance since 2015 for listed corporations in China. We take the ESG scores lagging 1 year to eliminate endogenous interference, so the sample observation period of this article is 2016–2020. Second, the data on financial, insurance corporations and special treatment (ST) were removed. Finally, accessing firm-level ESG scores data is particularly difficult for non-listed corporations. We selected listed corporations on the Shanghai and Shenzhen Stock Exchanges. In general, our final sample consists of 2,781 observations. We obtain ESG score and bond data from the Wind database and extract financial and corporate data from the China Stock Market and Accounting Research Database (CSMAR).

4.2 Models and variables

Following a previous study (Schwert, 2017), we test the relationship between ESG scores and Spreads with the following model:

$$\begin{aligned} Spreads_{i,t} = {} & \beta_0 + \beta_1 Scores_{i,t-1} + \beta_2 BondSize_{i,t} + \beta_3 IssuerRating_{i,t} \\ & + \beta_4 BondTerm_{i,t} + \beta_5 SOE_{i,t-1} + \beta_6 ROA_{i,t-1} + \beta_7 Coverage_{i,t-1} \\ & + \beta_8 Leverage_{i,t-1} + \beta_9 Z\_Score_{i,t-1} + \beta_{10} TopTenSquare_{i,t-1} \\ & + \beta_{11} Assets_{i,t-1} + \sum_{1}^{2} \gamma_k RateType_{i,t} + \sum_{1}^{4} \delta_j BondType_{i,t} \\ & + \sum_{1}^{21} \lambda_n Industry_{i,t-1} + \sum_{1}^{5} \theta_m Year_{i,t} + \mu \end{aligned}$$

We use Spreads, the initial bond yield spreads, as a proxy for the dependent variable. Scores are independent variable. Following previous analysis (Deng and Cheng, 2019; Broadstock et al., 2021; Xu et al., 2021), we used SynTao Green Finance ESG scores index (ST-ESG), and sorted from low to high based on the sample level, D is the lowest level and is measured 1, and the rank is changed by 1, A+ level is measured 10 (Cornaggia et al., 2017; Ali et al., 2019). Table 1 provides the variables in the regression model.

4.3 Descriptive statistics

Table 2 lists the summary statistical results of the variables for the entire sample. The average Spreads of bonds are 1.430 and the median Spreads are 1.090, which shows that the interest rate is significantly higher than the treasury bond of the same period, the risk premium is significant. The average ESG scores is 5.200, and the median ESG scores is 5.000, which indicates that the ESG scores of bond issuers are generally low in China. In addition, the statistical results of the control variables also well reflect status of corporate bond issuance. Turning to bond characteristics, the large individual differences in scale and maturity show that companies have significantly different bond issuance capabilities and needs. The solvency and profitability of issuing bond companies are also different. Furthermore, SOEs comprise 74% of the sample, indicating that most bond issuance companies with ESG reporting are state-owned in China.

TABLE 1 Variable definitions.

Variables	Description
Spreads	Coupon rate minus Treasure bond yields of comparable maturity
Scores	SynTao Green Finance ESG Scores index
BondSize	Bond financing scale (RMB 100 million yuan)
IssuerRating	An ordered variable, with 3 for an AAA Scores; 2 for AA; 1 for otherwise
BondTerm	The maturity of corporate bonds
BondType	the sample includes different bond type (corporate bond; enterprise bond;medium-term note bills; (ultra) short term financing bonds), When the observation value belongs to a certain type, the value is 1 and zero for otherwise
RateType	Interest rate type is 1; fixed rate is zero
SOE	The final control is state-owned, taking the value for 1 and zero for otherwise
ROA	Total assets remuneration rate
Coverage	Interest security multiples
Leverage	Total closing liabilities/final total assets
Z_Score	Altman's Z-Score model in 1968, which proxies for borrower's default risk
TopTenSquare	Top 10 shareholders (percentage)
Assets	Total assets at the end
Industry	When the corporate belongs to an industry, the value is 1; zero for otherwise
Year	When the corporate belongs to 1 year, the value is 1; zero for otherwise

Data source: Text collation.

TABLE 2 Descriptive statistics.

Variables	N	Mean	Min	Median	Max	Std dev
Spreads	2781	1.430	0.002	1.090	5.840	1.120
Scores	2781	5.200	3.000	5.000	8.000	1.110
BondSize	2781	14.600	0.300	10.000	150.000	12.400
IssuerRating	2,781	2.710	2.000	3.000	3.000	0.452
BondTerm	2781	2.070	0.041	0.740	15.000	1.940
SOE	2,781	0.739	0.000	1.000	1.000	0.439
ROA	2781	0.053	−0.068	0.047	0.225	0.029
Leverage	2781	0.644	0.149	0.664	0.917	0.130
Coverage	2781	13.600	−23.300	4.140	551.000	54.400
Z_Score	2781	1.640	0.139	1.260	24.400	1.370
TopTenSquare	2781	0.209	0.017	0.194	0.566	0.121
Assets	2,781	191.000	3.710	111.000	1056.000	233.000

Data source: Text collation. The same below.

TABLE 3 Correlation analysis.

Variables	Spreads	Scores	BondSize	IssuerRating	BondTerm	SOE	Coverage	Assets
Spreads	1	−0.268***	−0.302***	−0.492***	0.414***	−0.482***	0.044**	−0.252***
Scores	−0.238***	1	0.117***	0.181***	−0.190***	0.100***	−0.113***	0.097***
BondSize	−0.255***	0.085***	1	0.508***	0.061***	0.332***	−0.085***	0.601***
IssuerRating	−0.510***	0.179***	0.375***	1	−0.042**	0.412***	−0.014	0.618***
BondTerm	0.209***	−0.140***	0.100***	0.052***	1	−0.095***	0.101***	0.042**
SOE	−0.550***	0.092***	0.267***	0.412***	−0.022	1	−0.271***	0.270***
Coverage	−0.013	−0.02	−0.022	0.028	0.012	−0.219***	1	−0.026
Assets	−0.176***	−0.037*	0.472***	0.389***	0.177***	0.235***	−0.017	1

4.4 Correlation analysis

Table 3 reports the correlation matrices for critical variables used in this study. Spearman correlations above diagonal, Pearson correlations below diagonal. Spreads are significantly correlated with scores in the expected direction, and firm characteristics variables with Spreads are consistent with the findings of previous researchers. Such as, the nature of property rights has a significant negative correlation with Spreads, showing that State-owned enterprises possess "priority" in bond financing and the pricing is decreased due to implicit guarantees. The correlation between bond characteristics and Spreads also conforms to reality.

5 Empirical evidence

5.1 Baseline results

The results of our hypothesis are reported in Table 4 Panel A. The coefficient of ESG scores is -0.087 at 1% significance level, which indicates that ESG scores significantly reduced bond issuance risk premium. Therefore, the main hypothesis is verified.

5.2 Robustness tests

ESG scores difference test. We set dummy variables according to whether the listed company disclosed ESG scores, and if the corporation had disclosed ESG scores for SynTao Green Finance with one; otherwise, it is zero. As shown by the significantly negative coefficient on scores in the first column of Panel B Table4, it indicates that the risk premium of bonds is reduced significantly when ESG scores are disclosed. Obviously, ESG scores supply incremental information.

Replace explanatory variables. We used the ESG scores of Hua Zheng and MSCI as the explanatory variables to ensure the reliability of explanatory variables. MSCI ESG scores are also authoritative and highly credible, and widely used in investment decision-making. We used Python to request ESG scores for 2016 to 2020 from MSCI's official website. As shown in columns 2–3 of Panel B Table4, the impact of ESG scores on the risk premium still exists.

5.3 Endogeneity test

Using 2SLS procedure. We used the 2SLS procedure to alleviate the endogeneity problem. Referring to prior studies (Lin et al., 2012; Liu et al., 2019; Yang et al., 2021), our paper selected the mean values of the ESG scores in the same industry and year as instrumental variables, and carried out the 2SLS procedure. The results indicate that the coefficient of Scores in Table 5 PanelA is -0.093 and significant.

Using a particular sample and exogenous event. We choose the bond issuers listed in both Chinese mainland and Hong Kong as a particular sample. With the first revision of the Environmental, Social and Governance Reporting Guide completed by the Hong Kong Stock Exchange in 2017, the requirement for ESG information disclosure of Hong Kong-listed companies was raised to the level of "interpretation without disclosure", which further strengthened the market attention of ESG information. Therefore, we use 2017 as the starting point for exogenous events (Post) to construct the interaction between exogenous events and ESG scores (Scores_Post), and investigate the impact of exogenous events on the ESG scores effect. As reported in Table 5 PanelB, At the significance level of 5%, the coefficient of Scores_Post is -0.076, meaning that the ESG Scores indeed influence the bond premium and will change with the trigger of exogenous events.

TABLE 4 Baseline regression and robustness tests.

	Panel A	Panel B		
	(1)	(1)	(2)	(3)
Scores	−0.087***			
	(−6.74)			
Scores_Du		−0.077**		
		(−2.29)		
Scores_HZ			−0.087***	
			(−5.47)	
Scores_MS				−0.125***
				(−4.43)
BondSize	−0.002*	−0.004***	−0.003***	−0.002
	(−1.85)	(−3.41)	(−3.18)	(−1.01)
IssuerRating	−0.857***	−0.808***	−0.777***	−0.584***
	(−17.63)	(−21.92)	(−22.02)	(−4.42)
Ratetype	−0.078	−0.127**	−0.121**	−0.251*
	(−1.41)	(−2.57)	(−2.45)	(−1.94)
BondTerm	−0.064***	−0.127***	−0.122***	−0.011
	(−4.50)	(−8.26)	(−8.00)	(−0.49)
SOE	−1.109***	−1.027***	−0.993***	−1.322***
	(−21.47)	(−27.10)	(−25.45)	(−10.08)
ROA	−2.187***	−2.953***	−2.846***	−2.754*
	(−3.59)	(−6.28)	(−6.07)	(−1.82)
Leverage	1.557***	1.571***	1.542***	0.556
	(9.65)	(13.00)	(12.71)	(1.44)
Coverage	−0.001***	−0.001***	−0.002***	−0.002***
	(−5.59)	(−5.92)	(−6.42)	(−3.15)
Z_Score	−0.055***	−0.020	−0.018	−0.080*
	(−3.26)	(−1.64)	(−1.45)	(−1.68)
TopTenSquare	0.422***	−0.011	−0.042	1.042***
	(2.97)	(−0.09)	(−0.35)	(3.03)
Assets	−0.000***	−0.000***	−0.000***	-0.001***
	(−7.64)	(−7.29)	(−7.61)	(−5.27)
BondType	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Constant	4.374***	4.101***	4.613***	4.381***
	(21.39)	(26.69)	(27.24)	(9.84)

(Continued on following page)

TABLE 4 (*Continued*) Baseline regression and robustness tests.

	Panel A	Panel B		
	(1)	(1)	(2)	(3)
N	2781.000	4429.000	4407.000	778.000
adj. R^2	0.640	0.625	0.629	0.674

Note: T-statistics are in brackets. *, **, and *** indicate that the correlation is significant at 10%, 5%, and 1% levels, respectively. The same below.

6 Mechanism analysis

On the basis of information asymmetry perspectives, we examined the incremental information effect of ESG scores from two directions: the information disclosure of ESG behavior and the participation of financial intermediaries.

ESG Information Disclosure. We reflected the degree of information asymmetry based on the information disclosure of environmental, social and governance. Following Lanis and Richardson (2012) and Ali et al. (2022), we designed three variables for information disclosure of ESG behavior and reported measures of these three variables in the appendix (Table A1, Table A2, Table A3), then based on the annual industry average of each variable, we set three dummy variables EDummy, SDummy, GDummy (if the Environmental, Social, Governance is lower than the annual industry average respectively, EDummy, SDummy, GDummy with 1, otherwise it is zero). Table 6 Panel A reports that the interaction coefficients between each dummy variable and the explanatory variable are highly significant and negative, indicating that ESG scores' marginal effect is significant when less information disclosure on the environment, social responsibility, and governance.

Financial Intermediaries Participation. We also reflected the degree of information asymmetry from the perspective of financial intermediaries' characteristics and behavior. According to audit firm and analyst forecast dispersion, set two dummy variables NoBig10 and MeaFdisD (if an audit firm is not Big 10, NoBig10 with 1, otherwise it is zero; if the analyst forecast dispersion is greater than the mean, MeaFdisD with 1, otherwise it is zero). Table 6 Panel B shows that all the coefficients on scores_NoBig10 and scores_MeaFdisD are significantly negative, indicating that ESG scores marginal effect is significant when the audit firm is not Big 10 and higher analyst forecast dispersion. The above results show that ESG scores provide incremental information, thus providing investors with sufficient information on investment risk.

7 Additional evidence

7.1 Debt financing capabilities

The effect of ESG scores information may be heterogeneous with different debt financing capabilities. Usually, the companies which easier access to financing have low-risk premiums in the bond market, and higher ESG scores are difficult to reduce the risk premium. But other companies with poor debt financing capabilities are at a competitive disadvantage, generally difficult to obtain the recognition of investors. If these companies have excellent performance in non-financial aspects, such as ESG scores, may reduce investors' valuation of corporate risks to a great extent. We examine ESG scores effect on the companies which have different debt financing capabilities through the following four aspects:

Asset-liability ratio. Asset-liability ratio not only reflects corporate capital allocation, but also reflects the corporate debt risk. The higher debt ratio will increase the risk perceived by investors, which will weaken corporate debt financing ability;

Proportion of intangible assets. The high proportion of intangible assets will increase the risk of investors' evaluation of the company's value, thus aggravating the market information asymmetry. Moreover, from the traditional debt financing practice, compared with tangible assets, the mortgage ability of intangible assets is weak;

Firm size. The scale of a company can reflects comprehensive corporate strength. The smaller the scale, the weaker the anti-risk ability and the poorer debt financing capabilities;

Nature of property rights. In practice, non-state-owned holding companies are at a disadvantage in terms of development level, market recognition and trust. Therefore, the debt financing capabilities of non-state-owned holding companies were weaker than state-owned holding companies.

We divided groups by median asset-liability ratio, the proportion of intangible assets, firm size, as well as nature of property rights. The results of Table 7 Panel A to D indicate that ESG scores effect is significant when the company has a higher asset liability-ratio or proportion of intangible assets, smaller size and property rights is non-state-owned holding, The empirical results indicate that when debt financing capabilities are lower, the effect of ESG scores is positive.

7.2 Industry supervision and market monitoring

Corporations that are subject to industry supervision and market monitoring disclose a large amount of information to the

TABLE 5 Endogeneity test.

	PanelA:2SLS		PanelB: Exogenous events	
	(1)	(2)	(1)	(2)
Scores		−0.093**	−0.063***	−0.006
		(−2.16)	(−3.56)	(−0.20)
Scores_AVR	1.026***			
	(17.21)			
Scores_Post				−0.076**
				(−2.22)
Post				0.734***
				(3.89)
BondSize	0.010***	−0.002*	−0.001	−0.001
	(4.61)	(−1.67)	(−0.52)	(−0.46)
IssuerRating	0.498***	−0.854***	0.266	−0.026
	(9.16)	(−15.94)	(1.34)	(−0.12)
Ratetype	0.071	−0.078	0.447***	0.444***
	(1.08)	(−1.40)	(5.91)	(6.11)
BondTerm	−0.073***	−0.065***	−0.021	−0.005
	(−3.75)	(−4.48)	(−1.31)	(−0.29)
SOE	0.958	−2.185***	−0.639***	−0.640***
	(1.06)	(−3.61)	(−6.30)	(−7.32)
ROA	0.017	1.558***	−2.000**	−0.321
	(0.08)	(9.69)	(−2.15)	(−0.35)
Leverage	−0.002***	−0.001***	3.035***	4.081***
	(−3.80)	(−5.53)	(6.40)	(9.37)
Coverage	0.016	−0.055***	−0.011***	−0.006*
	(0.88)	(−3.25)	(−3.00)	(−1.81)
Z_Score	1.061***	0.428***	0.228***	0.306***
	(4.82)	(2.88)	(3.75)	(4.93)
TopTenSquare	0.047	−1.109***	0.280	0.435
	(0.91)	(−21.67)	(0.65)	(1.05)
Assets	−0.001***	−0.000***	−0.001***	−0.000**
	(−7.96)	(−6.64)	(−2.93)	(−2.15)
BondType	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Constant	−1.883***	4.392***	−1.927***	−2.497***
	(−4.81)	(19.45)	(−2.85)	(-3.75)
N	2781.000	2781.000	563.000	563.000
adj. R^2	0.327	0.640	0.696	0.718

(Continued in next column)

TABLE 5 (*Continued*) Endogeneity test.

public, and the incremental information effect of ESG scores is weakened. Heavy pollution industries have always received social attention and government supervision. The Chinese government has issued key monitoring lists for polluting corporations since 2010. From the perspective of information asymmetry, whether heavy pollution or key monitoring corporations, it is necessary to provide market investors with timely and sufficient information on business activities in strict accordance with regulatory regulations. In particular, key monitoring corporations also need to strictly follow relevant policies and regulations for disclosing information on pollution in detail. Investors pay more attention to these corporations and obtain relatively sufficient risk information. Therefore, the incremental information effect of ESG scores may be limited to investors.

Moreover, for heavy pollution or key monitoring corporations, they have had a considerable negative impact on the environment. Market investors believe that the investment of such corporations in environmental and social responsibility is in line with the expected obligatory behavior. However, in light pollution or non-pollution industries, these corporations are not subject to regulatory pressure on environment and social responsibility, if these corporations have positive signals in ESG performance, which will increase the market's recognition, so the incremental information effect of ESG scores may be greater.

We divided the sample into two groups with whether it was heavy pollution industries, then divide two groups with whether it was key monitoring. Table 8 presents the results and show that in the non-heavy pollution industry (non-key monitoring corporation) ESG scores have reduced the risk premium to a greater extent.

7.3 Bond default environment

When there are massive of defaults in the bond market, the positive effect of ESG scores will be more prominent. Frequent bond defaults cause investors to panic and lose confidence in the market. At that time, investors'demand for positive information increased and they will focus more on corporate quality. ESG scores focus on measuring the values and business paradigms, and evaluating the social value brought by the corporation.

TABLE 6 Mechanism analysis.

	Panel A: ESG information disclosure			Panel B: Financial intermediaries participation	
	(1)	(2)	(3)	(1)	(2)
	E	S	G	NoBig10	MeaFdisD
Scores	−0.044**	−0.050***	-0.051***	−0.064***	−0.049***
	(−2.49)	(−3.36)	(−3.24)	(−4.80)	(−3.30)
Scores_EDummy	−0.074***				
	(−3.12)				
EDummy	0.438***				
	(3.42)				
Scores_SDummy		−0.079***			
		(−3.37)			
SDummy		0.508***			
		(3.99)			
Scores_GDummy			−0.082***		
			(−3.29)		
GDummy			0.534***		
			(3.91)		
Scores_NoBig10				−0.127***	
				(−3.47)	
NoBig10				0.682***	
				(3.53)	
Scores_MeaFdisD					−0.144***
					(−5.62)
MeaFdisD					0.748***
					(5.28)
BondSize	−0.002*	−0.002*	−0.003**	−0.002*	−0.002**
	(−1.82)	(−1.88)	(−2.50)	(−1.95)	(−2.21)
IssuerRating	−0.905***	−0.860***	−0.839***	−0.855***	−0.855***
	(−17.54)	(−17.68)	(−17.27)	(−17.20)	(−17.74)
Ratetype	−0.043	−0.079	−0.096*	−0.082	−0.076
	(-0.76)	(−1.41)	(−1.74)	(−1.47)	(−1.38)
BondTerm	−0.067***	−0.061***	−0.048***	−0.063***	−0.062***
	(−4.71)	(−4.28)	(−3.39)	(−4.40)	(−4.30)
SOE	−1.054***	−1.084***	−1.034***	−1.090***	−1.114***
	(−19.91)	(−20.74)	(−19.69)	(−21.11)	(−21.76)
ROA	−2.032***	−2.112***	−2.347***	−1.985***	−2.432***

(Continued on following page)

TABLE 6 (*Continued*) Mechanism analysis.

	Panel A: ESG information disclosure			Panel B: Financial intermediaries participation	
	(1)	(2)	(3)	(1)	(2)
	E	S	G	NoBig10	MeaFdisD
	(−3.22)	(−3.50)	(−3.75)	(−3.29)	(−3.84)
Leverage	1.427***	1.447***	1.606***	1.528***	1.653***
	(8.61)	(8.83)	(9.54)	(9.46)	(10.40)
Coverage	−0.001***	−0.001***	−0.001***	−0.001***	−0.001***
	(−3.04)	(−5.45)	(−5.92)	(−5.71)	(−5.69)
Z_Score	−0.063***	−0.055***	−0.046***	−0.058***	−0.051***
	(−3.62)	(−3.20)	(−2.92)	(−3.38)	(−3.04)
TopTenSquare	0.402***	0.388***	0.720***	0.398***	0.430***
	(2.64)	(2.70)	(4.78)	(2.77)	(3.00)
Assets	−0.000***	−0.000***	−0.000***	−0.000***	−0.000***
	(−6.25)	(−6.63)	(−7.34)	(−7.31)	(−7.50)
BondType	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Constant	4.238***	4.154***	3.780***	4.241***	4.113***
	(19.12)	(19.68)	(16.67)	(19.85)	(19.61)
N	2530.000	2682.000	2614.000	2781.000	2781.000
adj. R^2	0.641	0.649	0.634	0.642	0.643

Although it is not a financial performance indicator, it has a certain early warning effect on corporate risks (Kanamura, 2021). Especially in the concept of global sustainable development, corporations increasingly consider ESG investment in daily operations, and it will help corporation improve Sustainable Business Performance. ESG scores information also include the behavioral information of corporate investment in green environmental protection, social and governance. Prior study has also shown that corporate social responsibility investment and higher levels of corporate governance can help reduce the default rate of corporate bonds. Therefore, when the market has a large number of bond defaults, ESG scores have a greater impact on bond risk premium.

We divided two groups with bond default in the Chinese market, Table 9 Panel A shows that in the gentle period of default, the regression coefficient of scores is 0.030 and not significant, but in the outbreak period of default, the coefficient of scores is −0.108 and highly significant, showing that ESG scores play a greater role in reducing the bond credit risk premium during the outbreak of default.

7.4 Annual trend change

Up to now, the ESG information disclosed by listed corporations still has no unified paradigm and caliber, while the ESG scores of financial institutions have high systematic and quantitative functions, which not only conform to today's macroeconomic development policies, but also provide timely and comparable information for investors. At the same time, the Chinese government has also attached importance to and issued ESG related green finance policies year by year, so investors have paid more and more attention to ESG scores.

Especially, given that the COVID-19 started in December 2019 in China, it has had a huge impact on the economy of China and the world. In the context of COVID-19 pandemic in 2020, Chinese government has put forward the strategic goal of emission peak and carbon neutrality to face the sustainable development, investors will attach more importance to ESG scores information to help them judge the long-term investment value and potential risks of the corporation.

TABLE 7 Debt financing capabilities regression.

	Panel A		Panel B		Panel C		Panel D	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
	Lev ≤ Median	Lev > Median	InTang ≤ Median	InTang > Median	Assets > Median	Assets ≤ Median	SOE	NoSOE
Scores	−0.074***	−0.081***	−0.035	−0.079***	0.002	−0.127***	−0.047***	−0.134***
	(−4.17)	(−4.38)	(−1.54)	(−4.85)	(0.15)	(−6.06)	(−4.15)	(−3.80)
BondSize	−0.002	−0.002	−0.003	−0.002	−0.001	−0.005	−0.002***	−0.007
	(−1.12)	(−1.36)	(−1.24)	(−1.60)	(−0.86)	(−1.12)	(−2.75)	(−1.11)
IssuerRating	−0.798***	−0.845***	−0.728***	−1.000***	−1.106***	−0.871***	−0.647***	−0.998***
	(−15.43)	(−9.19)	(−9.53)	(−16.23)	(−8.02)	(−13.99)	(−11.70)	(−9.37)
Ratetype	−0.085	0.097	−0.217**	0.155**	−0.036	−0.143	0.141***	−0.241*
	(−1.12)	(1.22)	(−2.45)	(2.36)	(−0.47)	(−1.54)	(2.59)	(−1.94)
BondTerm	−0.029	−0.067***	−0.082***	−0.038**	−0.032**	−0.102***	−0.024**	−0.051
	(−1.39)	(−3.65)	(−2.99)	(−2.39)	(−2.04)	(-3.08)	(−2.10)	(−0.99)
ROA	−1.734**	−5.060***	−4.210***	−1.027	−0.286	−2.762***	−1.199*	−3.719***
	(−2.35)	(−3.08)	(−4.20)	(−1.23)	(−0.24)	(−3.57)	(−1.93)	(−3.14)
Leverage	1.110***	1.037	1.398***	1.462***	0.521	1.526***	0.346**	3.819***
	(4.42)	(1.61)	(4.92)	(5.89)	(1.15)	(6.01)	(2.13)	(7.26)
Coverage	−0.001***	−0.002***	−0.002***	−0.003***	−0.002***	−0.001***	−0.001	−0.002***
	(−4.88)	(−3.53)	(−5.58)	(-6.19)	(−3.51)	(−4.52)	(−1.20)	(−5.15)
Z_Score	−0.070***	−0.080*	−0.067***	−0.042*	−0.207***	−0.036*	−0.083***	0.017
	(−3.12)	(−1.71)	(−3.00)	(−1.96)	(−3.18)	(−1.85)	(−3.96)	(0.68)
TopTenSquare	0.620***	−0.692**	−0.226	0.887***	0.280	−0.179	−0.453***	0.316
	(3.31)	(−2.52)	(−0.97)	(4.50)	(1.10)	(−0.91)	(−2.93)	(0.89)
Assets	−0.000***	−0.000***	−0.000***	−0.000***	−0.000***	0.004***	−0.000***	−0.002**
	(−3.77)	(−6.10)	(−4.48)	(−5.62)	(−4.77)	(3.47)	(−6.84)	(−2.48)
SOE	−0.753***	−1.474***	−1.336***	−0.996***	−1.506***	−0.902***		
	(−11.59)	(−15.20)	(−14.92)	(-12.94)	(−12.21)	(−12.83)		
BondType	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.802***	5.431***	4.586***	4.218***	5.702***	4.475***	3.214***	2.378***
	(13.23)	(8.95)	(14.89)	(13.81)	(10.38)	(14.14)	(15.20)	(3.85)
N	1379.000	1402.000	1394.000	1387.000	1401.000	1380.000	2055.000	726.000
adj. R^2	0.590	0.718	0.666	0.665	0.717	0.597	0.506	0.638

The five group regression results based on year are presented in Table 9 Panel B. The regression coefficients of scores in 2016 and 2017 are positive but not significant, and the regression coefficients of scores from 2018 to 2020 are negative and significant. Especially the rapid development of COVID-19 in 2020 affects the whole of China. Therefore,

TABLE 8 Industry supervision and market monitoring regression.

	Panel A		Panel B	
	(1)	(2)	(1)	(2)
	Non-heavy pollution industry	Heavy pollution industry	Non-key monitoring company	Key monitoring company
Scores	−0.140***	0.018	−0.118***	−0.035
	(−7.46)	(0.99)	(−5.58)	(−1.62)
BondSize	−0.001	0.000	0.000	−0.001
	(−0.66)	(0.04)	(0.08)	(−0.87)
IssuerRating	−0.871***	−0.834***	−0.897***	−0.835***
	(−14.91)	(−9.20)	(−13.21)	(−9.02)
Ratetype	−0.088	−0.004	−0.053	0.157*
	(−1.22)	(−0.05)	(−0.68)	(1.68)
BondTerm	−0.080***	−0.031*	−0.060***	−0.065***
	(−3.60)	(−1.74)	(−2.97)	(−2.73)
SOE	−1.127***	−0.938***	−1.096***	−0.762***
	(−19.53)	(−8.26)	(−16.41)	(−7.04)
ROA	−1.990**	−0.779	−1.427	−3.833***
	(−1.98)	(−0.87)	(−1.43)	(−4.18)
Leverage	1.869***	0.199	1.581***	1.265***
	(9.21)	(0.63)	(6.56)	(4.86)
Coverage	−0.001***	−0.007**	−0.001***	0.001
	(−5.39)	(−2.38)	(−2.96)	(0.73)
Z_Score	−0.044**	−0.179***	−0.061***	−0.053
	(−2.38)	(−2.86)	(−3.36)	(−1.23)
TopTenSquare	0.267	0.083	0.288	−0.241
	(1.56)	(0.39)	(1.42)	(−1.04)
Assets	−0.000***	−0.001***	−0.000***	−0.001***
	(−6.60)	(−6.38)	(−5.45)	(−4.07)
BondType	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Constant	4.848***	5.044***	4.631***	3.885***
	(18.89)	(14.17)	(15.65)	(11.45)
N	1813.000	968.000	1379.000	952.000
adj. R^2	0.645	0.615	0.650	0.665

investors pay more attention to ESG scores than before, which also showed that investors care more about value investment and also generate more risk aversion needs. The regression coefficient of scores is -0.193 in 2020, and is the most significant, showing that the impact of ESG scores on bond risk premium is prominently reflected in 2020.

TABLE 9 Annual trend change regression.

	Panel A		Panel B				
	Gentle	Outbreak	2016	2017	2018	2019	2020
Scores	0.030	−0.108***	0.034	0.028	−0.080**	−0.064**	−0.193***
	(1.25)	(−7.07)	(1.08)	(0.67)	(−2.46)	(−2.36)	(−7.74)
BondSize	−0.003*	−0.002*	−0.004*	−0.009***	−0.001	−0.001	−0.003
	(−1.81)	(−1.77)	(−1.87)	(−2.81)	(−0.32)	(−0.58)	(−1.35)
IssuerRating	−0.755***	−0.922***	−0.742***	−0.646***	−0.851***	−1.033***	−0.791***
	(-8.46)	(−17.03)	(−6.59)	(−4.45)	(−7.67)	(−10.86)	(−9.39)
RateType	−0.122	−0.026	−0.337**	0.410***	0.160	−0.061	−0.105
	(−1.37)	(-0.40)	(−2.57)	(3.33)	(1.36)	(−0.58)	(−0.88)
BondTerm	−0.052*	−0.048***	−0.087**	0.106**	−0.075*	−0.031	−0.023
	(−1.81)	(−2.94)	(−2.37)	(2.13)	(−1.88)	(−1.43)	(−0.77)
ROA	−1.638	−2.217**	−0.768	−0.741	−1.041	−4.068***	−2.997**
	(−1.63)	(−2.46)	(−0.51)	(−0.46)	(−0.50)	(−2.69)	(−1.97)
Leverage	1.142***	1.475***	1.538***	1.212**	1.427***	2.101***	0.979***
	(4.57)	(7.74)	(4.72)	(2.24)	(2.79)	(7.13)	(3.54)
Coverage	0.001*	−0.002***	0.000	0.000	−0.007*	−0.001	−0.002***
	(1.84)	(−5.79)	(0.15)	(0.14)	(−1.68)	(−0.77)	(−4.76)
Z_Score	−0.022	−0.078***	−0.013	−0.010	−0.081*	0.016	−0.097***
	(−1.26)	(−3.23)	(−0.63)	(−0.21)	(−1.66)	(0.35)	(−2.64)
TopTenSquare	0.171	0.260	0.786**	−0.773*	0.221	0.068	0.363
	(0.70)	(1.50)	(2.41)	(−1.92)	(0.53)	(0.22)	(1.53)
SOE	−0.761***	−1.244***	−0.885***	−0.703***	−1.253***	−1.314***	−1.152***
	(−8.55)	(−20.28)	(−7.17)	(−5.61)	(−11.12)	(−12.70)	(−11.55)
Assets	−0.000***	−0.000***	−0.000***	−0.001***	−0.001***	−0.000**	−0.000**
	(−3.69)	(−5.51)	(−2.71)	(−2.79)	(−5.54)	(−2.30)	(−2.22)
BondType	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes					
Constant	3.568***	5.126***	3.663***	2.850***	4.885***	4.872***	5.581***
	(10.11)	(22.73)	(8.36)	(4.85)	(9.72)	(13.72)	(14.32)
N	714.000	2067.000	449.000	265.000	512.000	711.000	844.000
adj. R^2	0.640	0.672	0.600	0.683	0.679	0.721	0.617

8 Discussion

1) **The purpose of this paper** is to explore the relationship between the ESG scores of bond issuers and the risk premium of bond issuance. Based on the ESG scores and bond issuance data of Chinese listed corporations, we empirically tested the relationship between them by referring to Lin et al. (2012) and Schwert (2017), and find that ESG scores can significantly

reduce the risk premium of corporate bond issuance. The results of this paper not only help to enrich the research on the economic consequences of ESG scores, but also help to expand the related research on the influencing factors of corporate bond financing cost.

2) This paper further confirms the incremental information value of ESG scores through the bond market. From the perspectives of the disclosure of corporate ESG behavior and the participation of financial intermediaries, this paper carried out the mechanism test, and further proved it through different scenarios of investors' information needs. Compared with previous studies, this paper based on the bond market can further enrich the research that discusses the incremental information value of ESG scores.
3) **This paper may have some limitations.** First, as financial institutions only issue ESG scores for listed corporations, the study sample in this paper are only listed corporations, so there is a potential problem of insufficient sample size. Second, the research scenario of this paper is Chinese capital market, so the research results are more applicable to emerging market.
4) **In future research**, we can not only focus on the study of ESG scores adjustment but also carry out related research from the perspective of E (Environment), S(Society) and G (Government) scores respectively, so as to build a more complete research system.

9 Conclusion

Using the ESG scores and the bond data of Chinese listed corporations, we empirically investigated the effect and internal mechanism of ESG scores on risk premium of bond issuance. First, we conclude that when the ESG scores of a bond issuer are higher, the investors will require a lower risk premium. Second, the results of the mechanism and further study indicated that the ESG scores can provide incremental information value to investors. Finally, based on the Chinese bond financing market, this study not only promote the expansion of ESG theory, but also proves that ESG scores information contributes to the development of capital market.

10 Implications

First, it provides empirical evidence for the application of ESG concept in global capital markets. As an emerging economy, China has a large bond market, but does not have a higher level of market-oriented pricing. But we have obtained very significant results, indicating that the ESG scores have indeed been widely used in the capital market. Second, corporations need to pay attention to their ESG scores. Based on the impact of ESG scores on financing costs they should establish ESG concept, improve ESG performance, and increase ESG information disclosure, so as to obtain higher ESG Scores from the third-party financial institutions. Finally**,** ESG scores provide investors with important incremental information about the issuing corporation, therefore ESG scores have important reference significance for investors to allocate investment products.

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

CZ: Conducted funding acquisition and methodology. LG: Conducted formal analysis. WW: Lead the writing and literature review. XC: Lead the data curation and literature review. JA: Leads the writing and the review.

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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

TABLE A1 Definitions of environmental performance variables.

Accounting method	Variable definition	
summary scores by item/theoretically optimal scores	Annual report	1 mark for disclosure of environment-related information in annual reports of listed firms, 0 mark otherwise
	Social responsibility report	1 mark for socially responsible disclosure of environment-related information by listed firms, 0 mark otherwise
	ISO14001 certified or not	1 mark for passing ISO14001 audit, 0 mark otherwise
	Environmental protection concept	1 mark for disclosing the firm's environmental protection philosophy, environmental policy, organizational structure of environmental management, circular economy development model, green development, *etc.*, 0 mark otherwise
	Environmental management system	1 mark for disclosing that the firm has developed a series of management systems such as relevant environmental management systems, regulations and responsibilities, 0 marks otherwise
	Environmental education and training	1 mark for disclosure of environmental related education and training in which the firm is involved, 0 mark otherwise
	Environmental emergency	1 mark for disclosure of the firm's establishment of an emergency response mechanism for major environment-related emergencies, emergency response measures taken, treatment of pollutants, *etc.*, 0 mark otherwise
	Implementation of the "three simultaneous" policy	1 mark for disclosure of the firm's implementation of the "three simultaneous" system, 0 mark otherwise

TABLE A2 Definitions of social responsibility performance variables.

Accounting method	Variable definition	
summary scores by item	Employee protection policy	Disclosure of employee protection, assigned a value of 1, otherwise 0
	Consumer protection policy	Disclosure of customer and consumer protection, assigned a value of 1, otherwise 0
	Stakeholder protection policy	Disclosure of shareholder protection, creditor protection and supplier protection assigned a value of 1, otherwise 0
	General social issues	1 mark for disclosure of public relations, philanthropy and social responsibility systems, 0 marks otherwise

TABLE A3 Definitions of corporate governance performance variables.

Variable name	Accounting method	Variable definition	
Governance	Step 1: we conduct principal component analysis and extract the first three principal components with eigenvalues greater than 1, so as to obtain the score of each principal component; Step2: the variance contribution rate of each principal component is taken as the weight, and then the weighted average summation method is used to calculate the total score	The largest shareholder shareholding ratio	The shareholding ratio of the largest shareholder
		Degree of equity concentration	The ratio of the shareholding ratio of the largest shareholder to the second largest shareholder
		Number of shareholder meetings	The number of annual general meetings of shareholders held by the company
		Board size	Number of board members
		Equity checks and balances	Ratio of the sum of the shareholding ratio of the second to 10th largest shareholders to the shareholding ratio of the first largest shareholder
		Duality	1 mark for the chairman and CEO concurrently,0 mark otherwise
		Audit Opinions	1 mark for standard unqualified audit, 0 mark otherwise

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Environmental, social, governance risk *versus* cooperation models between financial institutions and businesses. Sectoral approach and ESG risk analysis

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Introduction: ESG risk and the business sector are essential in the process of adapting business models towards sustainability. The article aims to analyze ESG risk, taking into account these business sectors that are most affected by ESG risk, and to identify the relationship between ESG risk and cooperation models of financial institutions and companies (Anglo-Saxon/German-Japanese). The original research approach was based on including the financial system model in the analysis of ESG risk impact and the companies' methods of achieving sustainable business models with external funding.

Methods: The study is based on a two-stage analysis. First, fuzzy cognitive maps are used to evaluate the strength and direction of the relations between factors included in the companies' sustainable business models according to the business sectors. At the second stage, a correspondence analysis was carried out to distinguish four groups of companies' industries characterized by homogenous features related to the business sector, sustainable business model (SBM), and the way to transform to sustainability.

Results: Methods of achieving sustainability in companies' business models differ depending on business sectors. The "financial institution—company" cooperation model and recommendations were proposed.

Discussion: Financial institutions play a crucial role in financing the transition into sustainable business models. However, their impact differs depending on the business sector and the model of the financial system (bank or market oriented). The study assumes that the financial system model determines the form of cooperation between financial institutions and companies in the process of financing costs towards sustainability.

KEYWORDS

ESG risk, financial institutions, cooperation models, enterprises, sustainable business model

1 Introduction

The risk of non-financial factors, also known as ESG risk (Environmental, Social, Governance risk), has now become the leading type of risk affecting the operating activities of business entities (Global Risks Report, 2022). The strength and direction of the impact of this risk depend, *inter alia*, on the specificity of the activity and the industry in which a given entity operates (Sustainalytics, 2022). The consequences of ESG risk translate into financial performance, including profitability and financial liquidity, which makes it necessary to mitigate this type of risk (Friede et al., 2015). Enterprises take a series of measures to reduce their exposure to ESG risk by adjusting their business models towards sustainable business models (Clementino and Perkins, 2021).

Adjustment measures that businesses apply towards sustainability require funding, the amount of which often exceeds the entities' resources to be used for the purpose of such financing. Hence, the critical role of the financial market in ensuring financing of adjustment measures taken by businesses. Sectors that react to climate changes (e.g., agriculture, insurance) and changes in the natural environment, as well as industries that create negative externalities resulting in environmental degradation (e.g., mining, fuel, chemical industries), are particularly exposed to the impact of ESG risk (Sustainalytics, 2022). Similarly, business sectors sensitive to social threats, including health risk, which find it impossible to implement a remote form of work (tourism, hotel industry, gastronomy, construction) are exposed to ESG risk. Finally, the risk associated with digitalization and cybersecurity is worth mentioning, which applies to sectors using electronic service delivery channels and operating in the virtual space (Global Risks Report, 2022). Financial markets conditionally provide financial capital to businesses, which means that only businesses that meet specific criteria can obtain financing. Transformation and adjustment of business models of enterprises towards sustainability in terms of limiting the impact of ESG risk can be financed conditionally by the financial market in some cases (Urban and Wójcik, 2019; Clementino and Perkins, 2021).

Therefore, financial markets have a tangible impact on the adjustment measures taken by businesses. The conditions set by financial markets differ depending on the financial system model. In case of systems based on the financial capital of the banking sector, there are creditworthiness requirements, taking into account internal ESG-based ratings and ratings that incorporate ESG. In systems based on the money flowing from the capital market, the conditions apply to the disclosure of non-financial information and attitudes towards sustainability, reducing the carbon footprint expected by stakeholders (Urban and Wójcik, 2019).

There are the interlinkages between environmental, social, and governance risk and cooperation models between financial institutions and businesses. According to the law, regulations and recommendations, financial institutions and businesses are nowadays obliged to incorporate ESG factors and ESG risk in their decision making process. Being sustainable and spreading the sustainable behavior constitute a common goal of financial institutions and businesses. Sustainable financial institutions include ESG risk in their risk management system, strategies and policies, and as a result they mitigate ESG risk and create a sustainable value in their business models and impact on creation of the sustainable value of the companies' business models. Generally, the Anglo- Saxon model supports creation of the sustainable value in stock companies that gain financial capital from the capital market. The German—Japanese model is dedicated generally to traditional businesses with a limited access to the capital market because of disadvantages of using private placements. Green financial institutions deliver green financial solutions to the companies that tend to be green, are undergoing the transformation process or develop the green value and strengthen green solutions they have implemented. At the same time, the dirty sector is under the pressure to adjust and become green because the cost of cooperation and financing is much higher for these institutions because of the negative ESG risk assessment. Socially responsible financial institutions are open to cooperation with socially friendly businesses and they support solutions dedicated to reduce social exclusion. Finally, the governance factor is critical in ethical and responsible financial institutions that cooperate with businesses based on ethical codes but also taking into account board composition, pay parity or gender issues. The common pool in the cooperation models between financial institutions and businesses includes spreading of the sustainable behavior, creation of the sustainable value and designing of sustainable business models to support the implementation of sustainable development goals. The key actors in this process are stakeholders, especially governments responsible for creating the legal framework for sustainable development policies, financial markets and their intermediation rule and impact on spreading of the sustainable behavior, companies, households and NGOs.

Based on literature review, only two studies searching for a link between financial institutions (financial markets), corporate sustainability and sustainable business models have been published:

- Orlitzky et al. (2015) have searched the problem to what extent financial markets foster and facilitate more sustainable business practices?
- Muñoz-Torres et al. (2018) carried out the research entitled: Can environmental, social, and governance rating agencies favor business models that promote a more sustainable development?

The paper aims to draw attention to the significant gap in the existing research, along with the issues of impact of financial institutions on sustainable business models of the companies. To

the best of the authors' knowledge, no study has examined the relative importance of financial institutions of the company to adapt its business model. The novelty of the study is expressed by an original research approach based on inclusion of the financial system model in the ESG risk analysis in the context of sectoral enterprise analysis.

The purpose of the article is to analyze the ESG risk, taking into account the business sector most affected by this risk (the ranking) and to identify the correlation between this risk and the financial system model (Anglo-Saxon/German-Japanese). The research hypothesis assumes that the impact of ESG factors on companies' business models strongly depends on the type of financial markets (bank-based *versus* market-based) and the industry in which the company operates. The main objectives of the study include: 1. The analysis of the ESG risk by industry and financial systems models. 2. Development of a risk map and a cognitive map 3. Formulation of recommendations for the ESG risk management in the business sector 4. Development of a cooperation model between enterprises and financial institutions in the Anglo-Saxon and the German-Japanese models under the ESG risk conditions.

The paper is organized as follows: the introduction is Section 1; Section 2 contains a literature review. Section 3 presents the methodological approach, data collection procedure, description of the methods, and research results. Section 4 discusses the research results, and Section 5 offers cooperation models for "financial institutions and companies" in the ESG risk context. Section 6 is the conclusion.

2 Literature review

The Global Risks Report shows that the importance of environmental and social risk (i.e., non-financial risks) has increased in recent years compared to economic risk, and according to the latest report (World Economic Forum, 2022), this trend will continue to grow in the coming years. The concept of non-financial risk is defined in various ways in the literature. This risk is described as different from the financial risk and consisting of: operational risk, compliance risk, legal risk, model risk, strategic risk, IT risk, cybersecurity risk, third-party risk, and reputation risk (Deloitte, 2018). A similar approach was presented by Leo et al. (2019) who presented a risk taxonomy for banks. They distinguished financial and non-financial risk, where the latter includes: country risk, compliance risk, legal risk, conduct risk, model risk, business and strategic risk, strategic risk and operational risk, reputation risk. The risk of non-financial factors in the context of sustainable development should be interpreted more broadly, referring to the individual pillars of this development. In this context, non-financial risk is identified with ESG risk, i.e., risk caused by environmental, social and governance factors. With regard to financial institutions, the European Banking Authority defined ESG risk as "the risks of any negative financial impact on the institution stemming from the current or prospective impacts of ESG factors on its counterparties or invested assets" (EBA 2021).

Entities operating on the market are exposed to ESG risks to a different extent. The report "Understanding Materiality Lessons From Industries With High ESG Risk", shows that the five highest-risk industries in terms of ESG issues are industrial conglomerates, steel, diversified metals, precious metals, and oil and gas producers. In turn, the "The ESG Risk Atlas: Sector And Regional Rationales And Scores" report, indicates oil and gas extraction, mining, chemicals manufacturing, agribusiness or transportation as industries with the highest ESG risk.

ESG factors affect the functioning of entities in the real and financial spheres. Regulatory and market pressure, the growing awareness of the importance of ESG factors among capital owners, and the importance of these factors in the valuation of entity risk make the financial sector institutions incorporate non-financial factors into the business model and into investment and financial processes (Eccles et al., 2017; Grim and Berkowitz, 2020; Signori et al., 2021). Including ESG factors in the business model translates into an increase in banks' reputation (Dell'Atti et al., 2017; Forcadell and Aracil, 2017; Houston and Shan, 2019), financial stability (Chiaramonte et al., 2021) and better financial results (Brogi and Lagasio, 2019), e.g., an increase in ROA, ROE and Tobin's Q (Cornett et al., 2016; Miralles-Quirós et al., 2019; Nizam et al., 2019; Buallay et al., 2020). Positive influence of ESG factors on financial performance of banks manifests in loan growth (Nizam et al., 2019), while including these factors in lending decisions of a bank results in better financial performance (Ahmed et al., 2018). Gangi et al. (2019) showed that banks taking into account ESG factors have a lower level of risk, and the involvement of banks in ESG issues reduces their risk of insolvency (Neitzert and Petras, 2019).

A growing number of financial institutions include ESG factors in their decision-making processes (Busch et al., 2016; Ahmed et al., 2018; Inderst and Stewart, 2018). Investors on the capital market are increasingly willing to invest capital in sustainable financial products. Xiong (2021) revealed that achieved returns for stocks with low ESG risk rating (green stocks) are higher and they also provide improved tail-risk protection comparing to stocks with high ESG risk rating (brown stocks), particularly for the period of crisis caused by COVID-19. Maiti (2021) showed that for all cases, portfolios formed on social and governance factors provide better investment performance than traditional portfolios based on size and value.

The availability of consistent, comparable and reliable ESG information has become a prerequisite for making investment decisions (Hübel and Scholz, 2020). ESG ratings are helpful for investors in the investment process (Avetisyan and Hockerts, 2017). Unfortunately, rating agencies evaluate the corporate sustainability performance of a large number of companies,

however they use different sources of data and different methodology for analysis (Christensen et al., 2022). Chodnicka-Jaworska et al. (2021) showed a growing importance of the influence of ESG factors on credit ratings assigned to non-financial institutions by the leading credit agencies.

In the literature, there is a large number of studies devoted to the analysis of the impact (positive or negative) of ESG factors on the operations of enterprises (EBA 2021). The results of these studies show, that the inclusion of ESG factors in the business model has positive effect on the organization itself, i.e., operational efficiency (Whelan et al., 2021; Aroul et al., 2022), improvement of employee productivity (Henisz et al., 2019) and company's reputation (Dhaliwal et al., 2012), and an increase of company's competitiveness (Lundgren and Marklund, 2015). It also contributes to an increase of the market value of an enterprise (Ting et al., 2019; Wong and Zhang, 2022), higher stock price (Lo and Kwan, 2017; Bodhanwala and Bodhanwala, 2019), and higher financial ratios, such as ROA, ROE (Velte 2019; Peng and Isa, 2020). However, not all studies confirm a positive correlation between ESG factors and a company's financial performance. Duque-Grisales and Aguilera-Caracuel (2019) on the example of data on 104 multinational companies from Brazil, Chile, Colombia, Mexico and Peru between 2011 and 2015 showed a negative relationship between ESG and financial performance. Lee et al. (2009) also found that ESG investment decreases financial performance and argued that the result could show that cost of social capital for companies with high ESG scores is lower.

Incorporating ESG factors into the business model means transforming the business model towards a sustainable one. In the literature on the subject, there are many studies devoted to the analysis of the concept of the sustainable business model (Bocken et al., 2014; Nosratabadi et al., 2019; Goni et al., 2021), business model innovation for sustainability (Evans et al., 2017; Geissdoerfer et al., 2018; Shakeel et al., 2020), and tools to design and transform to sustainable business model (Merrilees and Marles, 2011; Høgevold et al., 2015; Geissdoerfer et al., 2016; Lüdek- Freund and Dembek, 2017; Sousa-Zomer and Cauchick-Miguel, 2017; Heyes et al., 2018; Morioka et al., 2018). Activities and practices are often the most important parts of business models, and business models can be seen as templates connecting company's strategy with practice, allowing to examine the value proposition, value creation, delivery, and capture (Osterwalder and Pigneur, 2010; Ritala et al., 2014).

The transition to a sustainable business model, very often requires to incur expenditures exceeding financial capabilities of an enterprise, hence the need for external financing. According to Schoenmaker (2017), the financial system which task is to allocate funding to its most productive use, plays a key role in allocation of investment funds and loans for the transformation of enterprises into sustainable ones. In cooperation with enterprises, financial institutions act as a capital provider (lender) and an intermediary on the financial market, supporting entrepreneurs in financing their economic projects. Previous research has focused on the analysis of the impact of ESG factors on the cost of raising capital. Henriksson et al. (2018) showed, that better ESG score allows companies to obtain cheaper loans, higher credit rankings and lower cost of equity capital. On a sample of 154 French ESG companies in the years 2015–2020, Chouaibi et al. (2021) showed that corporate social responsibility (CSR) activities lower the cost of equity capital, thus they are important to shareholders' financing and investment decisions. According to the results of research conducted by Raimo et al. (2020) the increase of ESG disclosure reduces the cost of equity capital. Eliwa et al. (2019), based on a study of loan institutions in 15 European Union countries, showed that firms with better ESG performance have a lower cost of debt, and that the impact of ESG disclosure on the cost of debt is equal to the impact of ESG performance. Apergis et al. (2022), based on the analysis of firms within S&P 500 over the period 2010–2019, revealed the relationship between the cost of debt for borrowing firms and their ESG score/rating. Firms with low ESG scores are associated with higher riski, which is results from higher cost of unsecured debt in the primary bond market. Scatigna et al. (2021) on the example of social bonds and conventional securities issued by banks and corporates between 2016 and 2021, demonstrated that investors wish to pay a premium for holding social bonds and that companies with higher carbon emissions are associated with higher credit risk and have slightly higher risk-adjusted debt financing costs.

Banks, through the cost of capital (Chava and Roberts, 2008; Nini et al., 2012), and investors in the capital market, can influence the behavior of companies. However, there are no studies on the impact on transforming the business model of enterprises towards sustainability depending on the model of the financial system (Anglo-Saxon/German-Japanese).

3 Research methodology

In this research on the impact of the ESG risk on the functioning and development of companies from the sectors selected for the survey, a two-stage research procedure was employed (Figure 1).

The first stage of the research involved structuring the research problem. It aimed at recognising the direction and strength of the relations between the factors included in the sustainable business models. For this purpose, the study used Fuzzy Cognitive Maps (FCM). A detailed description of this quite new method and examples of its implementation for structuring research problems can be found in the following publications: Andreou et al. (2003), Andreou et al. (2005), Tan and Ozesmi (2006), Wei et al. (2008), Salmeron et al. (2012), Papageorgiou et al. (2009), Furfaro et al. (2010), Song et al. (2010), Papageorgiou and Salmeron (2012), and Zioło et al. (2019).

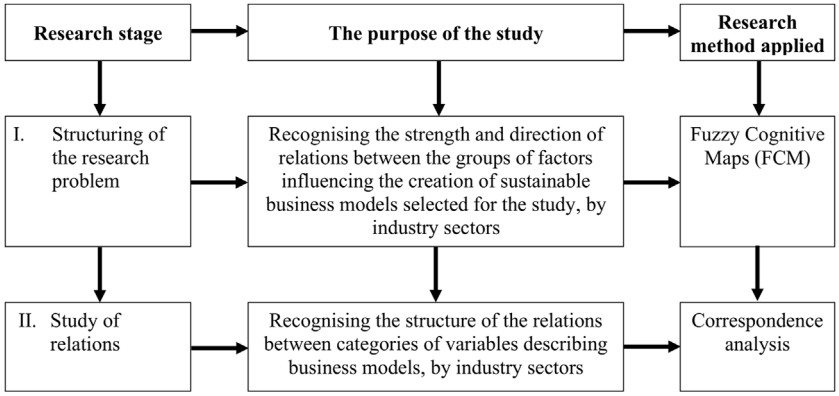

FIGURE 1
Organization of the research, Source: own elaboration.

FCM is a tool that allows analyzing of dependencies (connections) between the main factors (variables) of the considered phenomenon. This method allows indicating, both the direct relations and indirect with other analyzed criteria. One of the main effects of this procedure is also the assessment of the impact of the system constructed in this way on the examined phenomenon. The identification of the relations is very often carried out using the expert approach, based on the Delphi method and some relatively simple calculation procedures (cf. Słoń and Yastrebov, 2011). In the first step, the list of starting factors explaining the examined phenomenon should be established based on the results of research conducted among employees of companies representing various sectors affected by the occurrence of ESG risk. In the next step, the selecting criteria of the greatest importance for the created final model of examining dependencies was carried out. Finally, a matrix of co-dependencies between the examined criteria was prepared. The relations between analyzed criteria were prepared in form of maps. The thus obtained maps were analyzed based on their density and types of factors presented on the maps. The density of the fuzzy cognitive map (D) is estimated by a connection index which shows the way in which the analyzed factors on the map are connected (Ozesmi and Ozesmi 2004). To determine the coefficient of grouping, the study used a formula in which the number of the existing connections on the map was divided by the maximum possible number of connections that can occur between the analyzed factors (Hage and Harary, 1983):

$$\boldsymbol{D} = \frac{\boldsymbol{C}}{\boldsymbol{N}(\boldsymbol{N}-\boldsymbol{1})} \tag{1}$$

If the density of the map is high, one can observe a large number of relations between the factors. The map can show three types of factors: transmitter factors (T) which initiate relations with the remaining factors (enforcing functions); factors performing the role of receivers (R) to which the impact of enforcing functions is directed (utility factors); it is also possible to identify an independent set of factors made up of factors among which there are no relations. The complexity of the map is reflected by the total number of factors performing the role of a receiver (utility factors). If the map includes many factors and relations existing between them, its density is high. However, too large a number of factors playing the role of a transmitter could suggest an excessive "smoothness" of the map. It means a lack of relations among the factors and errors made in the process of identifying the factors describing the considered problem (Ozesmi and Ozesmi, 2004). To compare the complexity of the maps, the relations existing between the factors acting as receivers and transmitters are used:

$$\boldsymbol{complexity\ of\ a\ map} = \frac{\boldsymbol{R}}{\boldsymbol{T}} \tag{2}$$

In more complex maps, this coefficient would be larger due to the large number of relations between the examined factors.

In the second stage of the research, in order to identify the relations between the variables selected for the study which concern both sustainable business models and companies representing different sectors, a multiple correspondence analysis was used, which is a method from a group of multidimensional methods of examining coexistence. It can be successfully applied in questionnaire surveys because it solves one of the more difficult tasks, namely it allows to correctly recognize the structure of the answers, expressed by the frequencies of the coexistence of the individual categories of the characteristics measured on an ordinal or nominal scale, whilst not posing requirements as to the size of the set of statistical units. Its attractiveness results from the wide range of applications, and the possibility of a graphic presentation of the results. The starting point was the compilation of a complex contingency table (cross-tabulation), which contains the numerosity of occurrence of the individual categories of

variables selected for describing *n* objects. These numbers can be written down in the form of a complex matrix of indicators, multidimensional contingency table or a combined contingency table. In practice tasks, the Burt matrix is a frequently employed way of recording data. The procedure is carried out in the following stages (Greenacre, 1994, 2007; Beh and Lombardo 2014; Ginanjar et al., 2019):

1) Preparation of the Burt matrix; based on a symmetrical block matrix in which, apart from the main diagonal, there are contingency tables corresponding to two different variables, containing the numbers of objects with the categories of these two features.
2) Determination of the dimension of the real space of co-occurrence of the categories of variables *K* based on the formula:

$$\boldsymbol{K} = \sum_{q=1}^{Q}\left(\boldsymbol{J_q} - \boldsymbol{1}\right) \tag{3}$$

where.

J_q—number of categories of variable q (q = 1, 2, . . . , Q),
Q—number of variables;

3) Checking to what degree the eigenvalues (main inertias) of the space of a lower dimension, explain total inertia (λ)[1]; to this end the Greenacre criterion was used, which assumes that for the purposes of the research one accepts main inertias larger than a reciprocal of the number of the analyzed variables ($\frac{1}{Q}$);
4) Increasing the quality of representation in a two-dimensional space through a modification of eigenvalues according to Greenacre's proposal:

$$\tilde{\boldsymbol{\lambda}}_{\boldsymbol{k}} = \left(\frac{\boldsymbol{Q}}{\boldsymbol{Q}-\boldsymbol{1}}\right)^{2} \cdot \left(\sqrt{\boldsymbol{\lambda}_{\boldsymbol{B,k}}} - \frac{\boldsymbol{1}}{\boldsymbol{Q}}\right)^{2} \tag{4}$$

where.

Q—the number of analyzed variables;
$\lambda_{B,k}$—the *k*-th eigenvalue of matrix **B** (*k* = 1, 2, . . . , *K*),
$\sqrt{\lambda_{B,k}} = \gamma Bk$;
$\gamma_{B,k}$—the *k*-th singular value of matrix **B.**

5) Graphic presentation of the results of the correspondence analysis with the inclusion of the modification of eigenvalues. The new coordinate values are equal:

$$\tilde{F} = F^{\star} \cdot \Gamma^{-1} \cdot \tilde{\Lambda} \tag{5}$$

where:

$\tilde{F}$—the matrix of new coordinate values for variable categories;
F*—the matrix of original coordinate values for variable categories;
Γ^{-1}–the inverse diagonal matrix of singular values;
$\tilde{\Lambda}$–the diagonal matrix of modified eigenvalues.

If the space larger than three is the best form to present the coexistence of characteristics, then we need to select another method for analysing the results. For such purpose, in the space of both smaller and larger size we can apply the methods of classification. The categories of all analysed characteristics shall be defined as objects and the values of projection coordinates of each category are the variables. The methods of classification are also useful when the number of all options of characteristics is significant and the dispersion of points in the graph makes it impossible to distinguish the classes unambiguously.

4 Study results

4.1 The result of the structuring of the research problem—stage 1

The study aimed at evaluating the strength and direction of the relations occurring between the factors included in the sustainable business models (stage 1), considered three basic groups of factors, namely:

- Social, including respecting employee right and human rights (F1, group 1),

Haseeb et al. (2019) highlighted the importance of social factors in achieving sustainable competitive advantage and sustainable business results. The management of the company as well as its employees determine the goals of the organization and the ways of achieving them, including the pace and scope of implementation of the sustainable development concept (Paais and Pattiruhu, 2020). One of the key elements of a sustainable business model is innovation (Geissdoerfer et al., 2018). Maier et al. (2014) emphasized the importance of the human factor in the process of creating and implementing innovations in enterprises. Enterprises adopt a variety of human resource management strategies in implementing sustainable development. These strategies can significantly contribute to the success of the change management program by creating obstacles or facilitating the process (Ulus and Hatipoglu, 2016). The introduction of technological changes may cause fear and resistance among employees. Such behavior may be dictated by the fear of losing a job (displacing human labor by machines) or the change itself, i.e., anxiety resulting from the need to adapt to new working conditions (retraining) (Birkel et al., 2019). Therefore, the social and technological aspects in

1 Total inertia is a *K* sum of eigenvalues, where *K* is a measure of the real space of coexistence.

organizations are very often contrasted with each other. As a rule, in organizations where the human factor is important, the technological aspect is of secondary importance, and the introduction of modern technologies (e.g., digitization of processes) is treated as a way to facilitate the work of employees (Khan et al., 2015; Fernández-Macías 2018). The social aspect also translates into the company's product offer. There are two reasons for this, the first is the management staff and employees, who by creating the organizational culture, determine the company's goals and operating strategies (Kiesnere and Baumgartner 2019; Roscoe et al., 2019). On the other hand, increasingly aware consumers expect the replacement of the current offer with sustainable products (Franceschelli et al., 2018). The company's cooperation with financial institutions and CSR organizations is much less important for SBM.

- Organizational, including actions aimed at the digitalization of a company, elimination of energy waste, *etc.,* (F2, group 2),

SDGs set ambitious priorities for governments and businesses to drive the implementation of sustainable development up to 2030. Norström (2013), points out that these ambitious goals alone will not generate change, and specific adjustment processes are necessary, decisions must take into account specific factors and the impact of global, national and individual levels should be taken into account. Lüdeke-Freund (2010) and Bocken et al. (2014) pointed out that sustainable business models (SBM), apart from sustainable social development, are also able to ensure environmental sustainability. The literature on the subject indicates that SBM have been effectively contributing to reducing the harmful effects of business activities on the environment and society through providing solutions to help firms and institution meet their economic and sustainability goals simultaneously. (Nosratabadi et al., 2019; Sehnem et al., 2019) The environmental factor becomes significant for value building, contributes to technological changes, and thus the use of clean energy, the maximization of materials and energy efficiency, with an emphasis on repair and maintenance, as well as on renewable processes, waste reuse, or rational environmental management in the circular economy. The results of research Palata et al. (2016) over SBM highlight the value provided to customers and society through the combination of direct economic benefits and environmental impact. Upward and Jones (2015) demonstrated the importance of the environmental factor by examining the ontology of business models. They also showed that sustainability factors (including the environmental factor) can contribute to sustaining the possibility of flourishing (strong sustainability). Current changes in business models take into account the innovation ecosystem, including environmental changes, as indicated by (Stasiškienė et al., 2021). Apart from a network of relationships combining actors and objects that establish connections, both complementary and substitute, the environment also has a special meaning for this ecosystem. Adner (2006) Taking ESG factors into account in their activities gives companies the opportunity to change their current approach, contribute to environmental protection and create business value. The conducted research confirmed the importance of not only the circular economy, which contributes to the protection of the natural environment or sustainable management of resources, but also indicates that the society chooses those products and services that have been produced or delivered with respect for the environment (Senthil Kumar and Saravanan, 2019; Ziolo et al., 2021). The influence of the environment on defining the canvas of business model is of particular importance for the construction of SBM. As the research shows, the environmental factor has an impact on all components of the business model. (Nosratabadi et al., 2019) The US Environmental Protection Agency (EPA) indicates "Reduce the environmental impacts of materials across their life cycle" as one of the four primary objectives of circular economy, and only then indicates "Increase socioeconomic benefits" as an effect of this reduction. (U.S. EPA, 2015; Singer, 2017) Focusing business models on sustainability in many cases means implementing the idea of a circular economy, which forces a new approach to SBM. Summing up, for many years the society has been more willing to buy environmentally-saving products, therefore SBM has to take into account the environmental factor.

- Technological, including the introduction of technological innovation, friendly to society and the environment (F3, group 3).

Research on the factors influencing sustainable business models indicate the positive role of technology in this process. Comin et al. (2020) point out that SBMs are focused on direct participation of the stakeholders, especially users, and their role in building sustainable value. Comin et al. (2020) also indicate that SBMs are technology-based, and in this type of models, the use of clean energy, the maximization of materials and energy efficiency, with an emphasis on repair and maintenance, as well as on renewable processes, waste reuse, or rational environmental management are very often the priority. Baden-Fuller and Haefliger (2013) indicate that SBMs are essentially linked with technological innovations, however, the construction of the business model is separated from the technology. They formulate the relationship between the business model and technology in two directions. First, their research shows that business models make a link between technology and performance of the company. Second, the development of the appropriate technology is a matter of the decision as regards the business model concerning openness and users' involvement. Bidmon and Knab (2018) showed in their research that within social and technical regime, the existing business models hinder

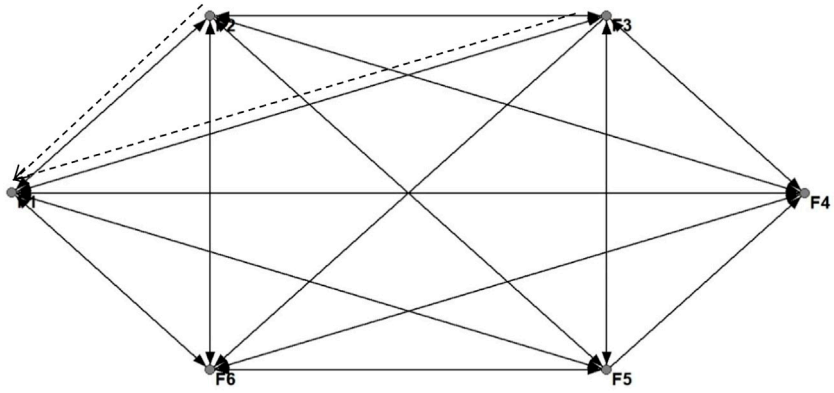

FIGURE 2
Collective FCM. Source: own elaboration.

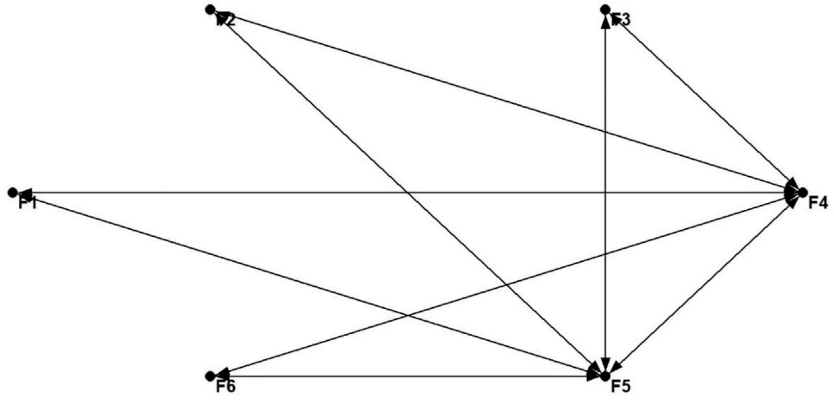

FIGURE 3
FCM for the agriculture sector, Source: own elaboration.

changes by strengthening the stability of the current system, as transitional products between a technological niche and the social and technical regime, business models drive the transition, facilitating the process of stabilizing technological innovations and their breakthrough from the niche to the regime level, and as a non-technological niche innovation, cutting-edge business models drive changes by building a significant portion of a new system without relying on technological innovations. Rantala et al. (2018) conducted research in which they investigated the relationship between sustainability and the adaptation of various innovation models. As a result, the research showed that a high rating of environmental sustainability reduces the contribution needed to adopt technological innovations, and the more an operator values institutional sustainability, the more likely it is to adopt the innovation in the business model. Carayannis et al. (2015) pointed to the effects that can be achieved thanks to business model innovations, in particular organizational durability. In addition, the research also took into consideration the policies implemented by the analyzed companies regarding:

- Offered products, including in their product range only those products which are friendly to society and the environment (F4, group 4),
- Cooperation with financial institutions, i.e., undertaking collaboration with environment-friendly financial institutions (F5, group 5),
- Cooperation with entities applying the strategy of corporate social responsibility (CSR), (F6, group 6).

A few variants of cognitive maps were prepared: a collective map (comprehensive) based on the information obtained from all representatives of the companies participating in the survey (Figure 2), and maps involving a division into the agricultural

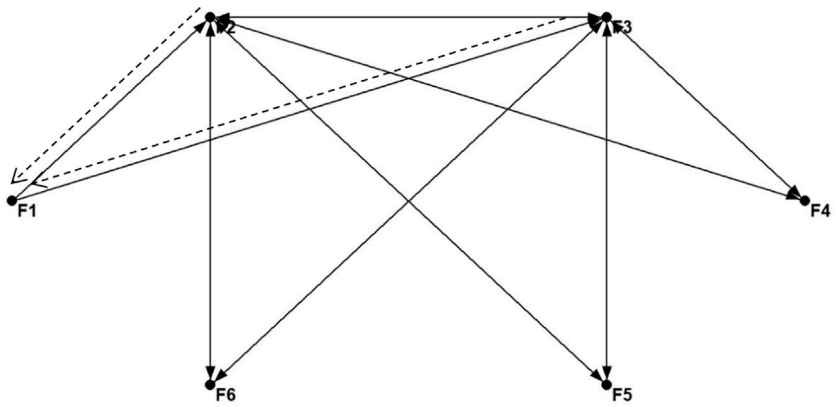

FIGURE 4
FCM for the industry sector, Source: own elaboration.

sector (Figure 3) and the industrial sector (Figure 4), for which there were identified differences in the evaluation of the relations given by those representing the examined companies. The sectoral maps showed only the strongest relations between the factors, additionally marking with a dotted line the negative relations between the analyzed factors. In the case of the service sector, no strong and repetitive relations were identified in the majority of the examined examples of the relations between the individual factors.

To build FCM, the study used the software FCMapper_bugfix_28.1.2022. The presented maps show the relations and directions of impact between individual factors. The demonstrated relations can be interpreted in the following way:

1) In the opinion of the surveyed representatives of companies, all the analyzed factors describing different sectors of the economy are interconnected. This means that they are significant in the creation of sustainable business models, creating a network of connections of a cause-and-effect nature.
2) In the constructed collective map, in total there were identified 28 connections between factors out of a possible 36, and its density amounted to 0.78, which means that specialists participating in the survey identified 78% of the connections from among all the relations which could theoretically occur in this map.
3) The identified connections are mostly positive (of a positive character), which indicates that an improvement in terms of one factor will positively influence another with which it is connected. In the collective map, there were identified 26 relations of this kind out of the 36 possible.
4) The negatively charged connections refer mainly to companies from the industry sector, whereas in general they were not observed in the case of the two other sectors (services and agriculture).
5) Not all the identified relations are bilateral in character. The improvement regarding factor F5 (factors regarding cooperation with financial institutions, namely those which are environment-friendly) will strongly positively impact on changes in factor F4, describing included in the range of products offered by the company only those which are friendly for society and the environment. The reverse relation of F4 influencing F5 was not observed.

4.2 The result of the correspondence analysis—stage 2

Statistical data for the research were taken from a questionnaire survey on the subject of business models, conducted in companies located in the Zachodniopomorskie and Lubuskie voivodeships in Poland.

The following variables and their categories were assumed in the study:

1) S—social factor, score from 1 (lowest) to 5 (maximum);
2) O—organizational factor, score from 1 (lowest) to 5 (maximum);
3) TF—technological factor, score from 1 (lowest) to 5 (maximum);
4) PS—offered range of products and services which are friendly to the environment and society, score from 1 (lowest) to 5 (maximum);
5) CFI—cooperation with environment-friendly financial institutions, score from 1 (lowest) to 5 (maximum);
6) CSR—cooperation only with entities applying CSR strategy, score from 1 (lowest) to 5 (maximum);

TABLE 1 Particular values and eigenvalues, together with the degree of explanation of the total inertia in the original and in the modified version.

K	Particular values γ_k	Eigenvalues λ_k	λ_k/λ	τ_k	$\tilde{\lambda}_k$	$\tilde{\lambda}_k/\tilde{\lambda}$	$\tilde{\tau}_k$
1	0,740911	0,548949	12,00,826	12,0083	0,4868	22,4224	22,4224
2	0,660331	0,436037	9,53832	21,5466	0,3645	16,7872	39,2096
3	0,555166	0,308209	6,74207	28,2886	0,2314	10,6573	49,8669
4	0,516717	0,266997	5,84055	34,1292	0,1902	8,7623	58,6293
5	0,473623	0,224318	4,90696	39,0362	0,1489	6,8587	65,4880
6	0,462812	0,214195	4,68551	43,7217	0,1393	6,4177	71,9057
7	0,446190	0,199086	4,35500	48,0767	0,1252	5,7682	77,6739
8	0,434337	0,188649	4,12669	52,2034	0,1156	5,3262	83,0001
9	0,421543	0,177699	3,88716	56,0905	0,1057	4,8689	87,8690
10	0,405953	0,164798	3,60495	59,6955	0,0942	4,3394	92,2084
11	0,400282	0,160226	3,50493	63,2004	0,0902	4,1543	96,3627
12	0,383729	0,147248	3,22105	66,4215	0,0790	3,6373	100,0000
					λ_k=2,1712		

7) Sectors: ONS—remaining sectors on non-material services (hairdressing, beautician, photography, and others), ONP—remaining sectors of material production (publications, films, information services and others), T—transport, TR—trade, C—construction, I—industry; H—healthcare and social security, HE—housing economy and non-material municipal services, OT—other sectors (finance and insurance, science and technology, physical culture, tourism and recreation, agriculture, arts and culture, municipal economy, schooling and education).

The correspondence analysis was carried out based on the Burt matrix sized 39 × 39 (number of variants of answers allocated to the seven selected questions in the survey). For the calculations and graphic presentation of the results, the study used the module *Correspondence analysis* in *Statistica 13.0*. The dimension of the actual space of coexistence amounted to 38—see Eq. 1. In the next step, it was checked to what degree the eigenvalues of a space with a lower dimension explain the total inertia (λ = 4.5714). In line with the Greenacre criterion, the main inertias larger than 1/Q = 1/7 = 0.1429 were accepted as relevant for the research. These were inertias for K assuming values up to 12, and this is why the results for K > 12 were omitted in the table, because for these dimensions the main inertias were not larger than 0.1429, and thus not relevant for the study.

Next, the study analyzed the values of measure τ_k which describes the share of inertia of the selected measure (λ_k) in the total inertia (λ), and it emerged that the degree of explaining inertia in a two-dimensional space amounted to 21.55%, while in three-dimensional space it was 28.29%. In order to increase the quality of representation, the modification of the eigenvalues was conducted according to Eq. 2. The original and the modified eigenvalues, together with the degree of explanation for the total inertia, are given in Table 1.

Following the conducted modification, the degree of explanation of total inertia for all the dimensions became clearly larger. In order to precisely define the dimension of the representation space, the graph of the eigenvalues was prepared, and using the "elbow" criterion it was shown that the space presenting the coexistence of the variants of the variables should be four-dimensional (Figure 5). The degree of explaining inertias in this space amounted to over 65.49%.

A direct interpretation of the results in a five-dimensional space is impossible. Such an interpretation can be made using the Ward method, which allows to establish connections among the variants of the variables. In Figure 6, showing the joining-up of categories into classes, the vertical line marks the stage in which this process was interrupted[2]. On the basis of the obtained classification, it was possible to distinguish four groups of sectors of the companies characterized by homogenous features (in brackets there are given variants of the categories of variables):

Group 1 (CSR5, CFI5, PS5, H, OT, TF5, O5, S5) comprises companies involved in healthcare and other sectors of business

2 To divide the dendrogram and determine the number of focal points, the following measure was used (Grabiński 1992): where d_i is i-th distance. The highest value q_i indicates the place of the dendrogram's division.

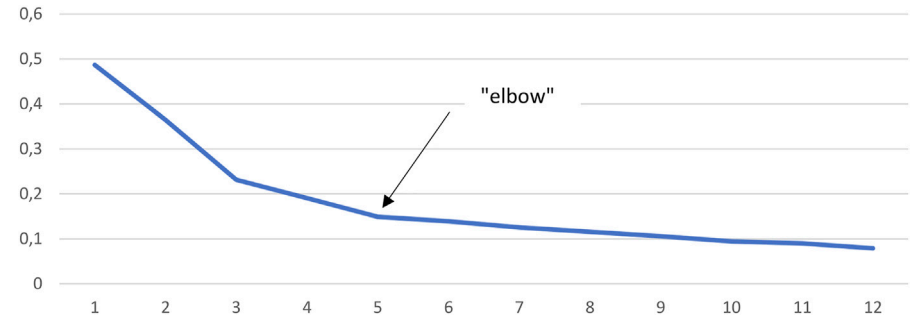

FIGURE 5
Eigenvalues, Source: own elaboration.

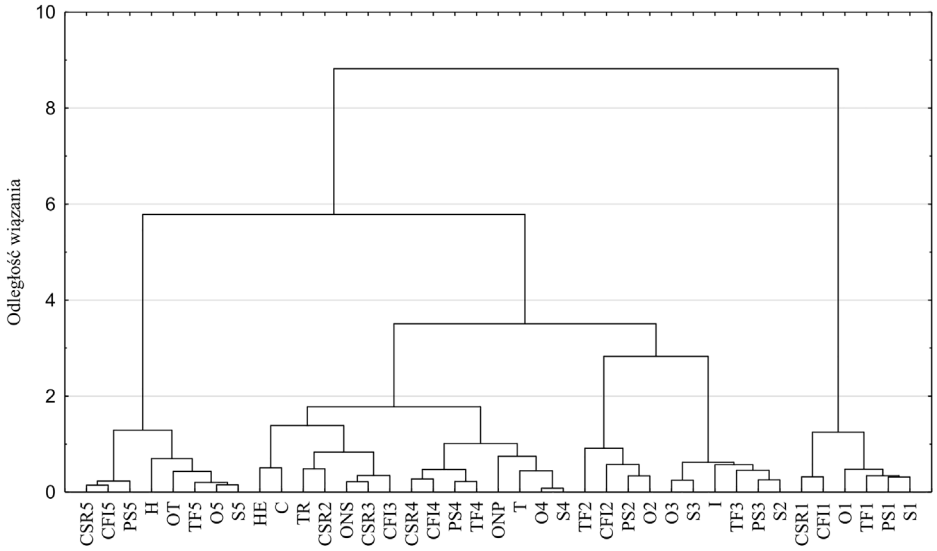

FIGURE 6
Diagram of a hierarchic classification of the categories of variables made according to the Ward method, Source: own elaboration.

activities (physical culture, tourism and recreation, science and development of technology, schools and education, finance and insurance, agriculture, municipal economy), which contribute in the highest degree to building a sustainable business model (maximum score) taking into consideration the following factors: social, organizational, and technological. Moreover, they offer products and services friendly to the environment and society, and also cooperate with financial institutions friendly to the environment and companies employing the CSR strategy.

Group 2 (HE, C, TR, CSR2, ONS, CSR3, CFI3, CSR4, CFI4, PS4, TF4, ONP, T, O4, S4) comprises companies from the following sectors: housing and non-material municipal services, construction, trade, other sectors of non-material services (hairdressing, beautician, photographic, and others), other sectors of material production (publications, films, information services, and others), transport. Companies from this group, when building sustainable business models, pay considerable attention to respect for the rights of employees (social factor), their organization is based on digitalization, they also introduce technological innovation friendly to the environment and society. They care about the cooperation with environment and society-friendly financial institutions and companies employing the CSR strategy.

Group 3 (TF2, CFI2, PS2, O2, O3, S3, I, TF3, PS3, S2) comprises industrial companies, which in building sustainable

business models—at the most to an average degree—take into consideration the social, organizational and technological factors. Moreover, their range of products and services which are friendly to the environment and society and their cooperation with the environment-friendly financial institutions, were assessed as below-average.

In group 4 there were no companies identified which in building sustainable business models would not take into consideration the social, organizational and technological factors. Moreover, they do not offer products and services friendly to the environment and society, and do not cooperate with environment-friendly financial institutions or companies employing the CSR strategy.

The first group of enterprises that undertake activities aimed at transforming their business model towards a sustainable business model to the greatest extent, includes enterprises from the agricultural sector. The obtained results are in line with the results of Ulvenblad et al. (2019). They included companies from the agri-food sector among entities which are increasingly required to adopt a sustainable business model. The transformation of these entities towards a sustainable business orientation is based on optimization and organizational transformation. Franceschelli et al. (2018), on the basis of an analysis of start-ups from the food industry, showed that the process of building sustainable business models is based on innovation and appropriate relations with stakeholders. Basile et al. (2021) drew attention to the importance of relations with stakeholders in the process of transforming the company towards sustainability. The study was conducted on the Italian offshore platform (oil and gas industry) located in the Adriatic Sea.

The first group of companies also includes companies from the IT sector. The results of the study contradict the results of the study by Egorova et al. (2022). They proved that IT industry demonstrates weak environmental and social components, and average governance component in comparison to other industries.

Industrial enterprises have been qualified among companies which, when building sustainable business models, take into account technological, organizational and social factors to a medium degree. Kita and Šimberová (2018), analysing Czech companies from the chemical industry, showed that companies striving to achieve a sustainable business model try to optimize the structure of costs, implement technological changes, maintain appropriate relationships with customers, which includes providing a support, sharing B2B resources and centralized waste processing.

Belyaeva et al. (2020), based on the example of European SMEs, examined the motivations of entities to transform business models towards sustainable models. In the case of companies from Eastern European, the main motivation were economic factors. In Western Europe, however, these were socio-cultural factors.

5 Cooperation models B2 (financial institution—companies). ESG risk analysis and recommendations

Risk maps were created to determine the probability and strength of the impact of ESG risks on enterprises. Definitions of risk types used to develop the risk maps are presented in Table 2. A total of 11 types of risk have been identified.

Using the types of risk presented in Table 2, separate risk maps were created for the German-Japanese and Anglo-Saxon banking systems. The risk map for the first one is shown in Figure 7.

In the German-Japanese banking system, the most important risks are reputational, operational, "double standards", physical, and liquidity risks. Tree of them have high impact as well as high probability of occurrence. Environmental risk is of medium importance together with regulatory, CSR, and compliance risks. The group of low risk consists of pandemic and stranded assets risks.

The risk map for Anglo-Saxon banking system is shown in Figure 8. For this model, four risk types are in the high-risk group, of which three are common to both models of banking systems: reputational, liquidity, and double standards risks. These risks are therefore of greatest importance to banking systems regardless of the model. In the Anglo-Saxon model the only medium risk is the risk of stranded assets. All other risks, including environmental and physical risks are classified as low.

The comparison of the risk maps for both banking system models shows that the Anglo-Saxon model seems generally more resilient. In this model, as many as six risks are of low importance, while in the German-Japanese model there are only two such risks. In contrast, there are more high risks in the German-Japanese banking system, although only one more than in Anglo-Saxon system.

The impact of environmental factors, especially SDGs risk, forces change in the business models of both financial institutions, including banks, and changes customers' business models. More and more often a business market advantage is perceived to be in sustainability, social responsibility or limiting ESG factors. Being sustainable is not only fashionable, but it also contributes to the fight against climate change. Both banks and their clients, when creating their business models and new values, perceive mutual cooperation as beneficial and are looking for common elements for running a business, or even a common ground of understanding for further cooperation, which is not always related to providing financing. These common elements are risk (including ESG risk as well as environmental and climate risk) and sustainability. Thus, the following spheres of influence of financial institution, which are represented both in the market-based financial system as well as in the bank-oriented financial system, on corporations should be

TABLE 2 Types of risk.

Risk name	Definition	Keywords
Reputation risk	Risk resulting from unfavorable perception by some stakeholders, that may negatively affect the bank's ability to establish or maintain business relationships and access to funds Basel Committee on Banking Supervision. (2009)	loss of image, loss of brand, loss of trust, trustworthiness
Risk of stranded assets	Risk associated with unanticipated or premature write-downs, devaluations, or conversion to liabilities' Caldecott et al. (2015), Stranded Assets and Subcritical Coal: The Risk to Companies and Investors, Oxford: Smith School of Enterprise and the Environment)	unanticipated or premature write-downs, devaluations, or conversion to liabilities, restructuration, transition to a zero-carbon economy, pro ecological technology
Liquidity risk	The risk of incurring losses resulting from the inability to meet payment obligations in a timely manner when they become due or from being unable to do so at a sustainable cost [https://coebank.org/en/investor-relations/risk-management/liquidity-risk/, Jaksybekova et al. (2018). Liquidity risk evaluation. Espacios, 39 (16), 1–18]	insolvency, untimely payment of liabilities
Physical risk (extreme weather events)	Risk associated with natural or weather-related disasters (Kron et al. (2019). Changes in risk of extreme weather events in Europe. Environmental Science & Policy, 100, 74–83.)The risks of any negative financial impact on the institution stemming from the current or prospective impacts of the physical effects of environmental factors on its counterparties or invested assets. [Arratibel (2020). 2020–10–15 BoS-ESG report MASTER FILEcl.]	extreme weather events, global warming, natural disasters
Regulatory risk	Risk arises when the interaction of uncertainty and regulation changes the cost of financing the operations of a firm (Ergas, Henry and Hornby, Jeremy and Little, Iain Robert and Small, John, Regulatory Risk (26 March 2001)	changes in legal regulations, cost of adjusting to regulations, cost of non-compliance with regulations, cost of compliance
Operational risk	The risk of negative financial consequences resulting from improper or failed internal processes or external factors (Basel Committee on Banking Supervision. 2006. The first pillar-minimum capital requirements. BIS consultative document)	device failures, damage to physical assets, employment issues, internal and external frauds
Pandemic risk	Pandemic risk is the expected value of the impact of widespread infectious disease in humans on human health, economies, and communities [Jonas (2013). Pandemic risk]	infection risk, health risk, difficulties and delays in production, difficulties in obtaining resources, costs of production, employment issue
Environmental risk	Risk related to the current or future impact of environmental factors on invested assets or contractors, causing a negative financial impact on the institution (EBA Report on management and supervision of ESG risks for credit institutions and investment firms EBA/REP/2021/18)	the effects of negative human impact on the environment, global warming, climate change, global warming, carbon footprint
Risk of CSR	Risk of not implementing effective CSR.	gender inequality, disrespect for human rights, not implementing or complying with the principles of corporate governance, lack of social commitment
Compliance risk	Compliance risk is the current and prospective risk to earnings or capital arising from violations of, or non-conformance with, laws, rules, regulations, prescribed practices, internal policies and procedures, or ethical standards. (EBA Guidelines on Internal Governance (GL 44)	risk of corruption, fraud, theft, bribery, money laundering and embezzlement
Risk of "double standards"	The risk of a different or more stringent application of the rules to different groups of people or circumstances	unequal conditions for the same group of customers, employees

Source: own elaboration.

seen from the viewpoint of changing and adjusting business models that result from canvas:

1) Typical (conventional) risk, which is assessed by financial institutions, including banks;
2) Environmental risk and ESG,
3) Business partners, including supplier policy;
4) Service and goods distribution channels;
5) Key activities/spheres of activity;
6) Customer segments;
7) Key/strategic resources.

Figure 9 presents the relationship between ESG risk—bank based model and ESG risk - market based model. The figure shows how the ESG risk affects the bank and market-based models and the company that must adapt to the changes caused by the ESG risk. The bank may stop servicing the enterprise and may also permanently limit access to its services and products.

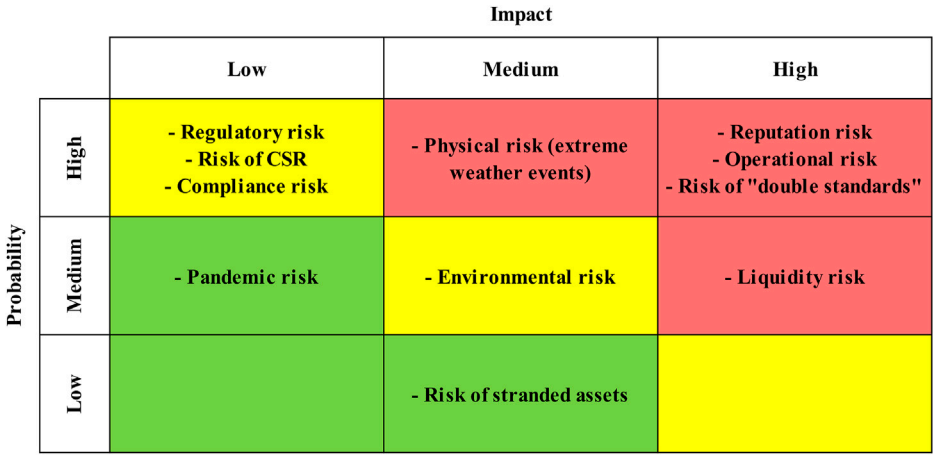

FIGURE 7
Risk map for German-Japanese banking system, Source: own elaboration.

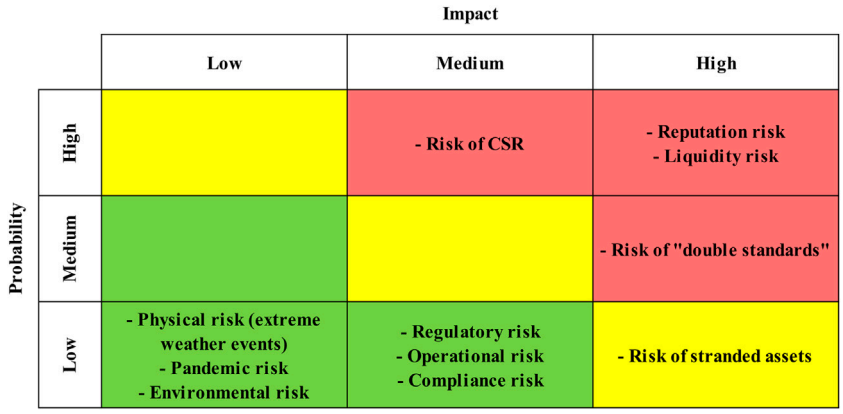

FIGURE 8
Risk map for Anglo-Saxon banking system, Source: own elaboration.

The market is open to enterprises, but there may be an outflow of capital from brown to green business. Lack of acceptance of the "brown" business may result in a reduction of assets. Financial institutions, in individual models, exclude from the market and service those enterprises that have the highest exposure to ESG risk. Thereby there is an influence on their behavior towards "green". A significant force influencing the changes towards "green" are shareholders, stakeholders and customers of enterprises. It is they who support the mitigation of ESG eye and show the lack of acceptance for its occurrence.

The indicated spheres of influence of financial institution on companies constitute this area, which becomes a kind of influence of the financial institution and banks on enterprises and enterprises on financial institution in the area of changes in the business model, in terms of sustainability. Mutual interactions between the financial system institutions and the enterprise, including stakeholders and risk in terms of the impact on business models are presented in Figure 10.

Figure 10 indicates that both financial institutions representing two financial systems (the market-based financial system as well as in the bank-oriented financial system) and clients (the enterprises) may influence the partner's business models under the influence of various factors related to sustainability and risk. With the move towards sustainability, financial institutions need to consider ESG and environmental risks. Their client is also exposed to this spectrum of risk, and

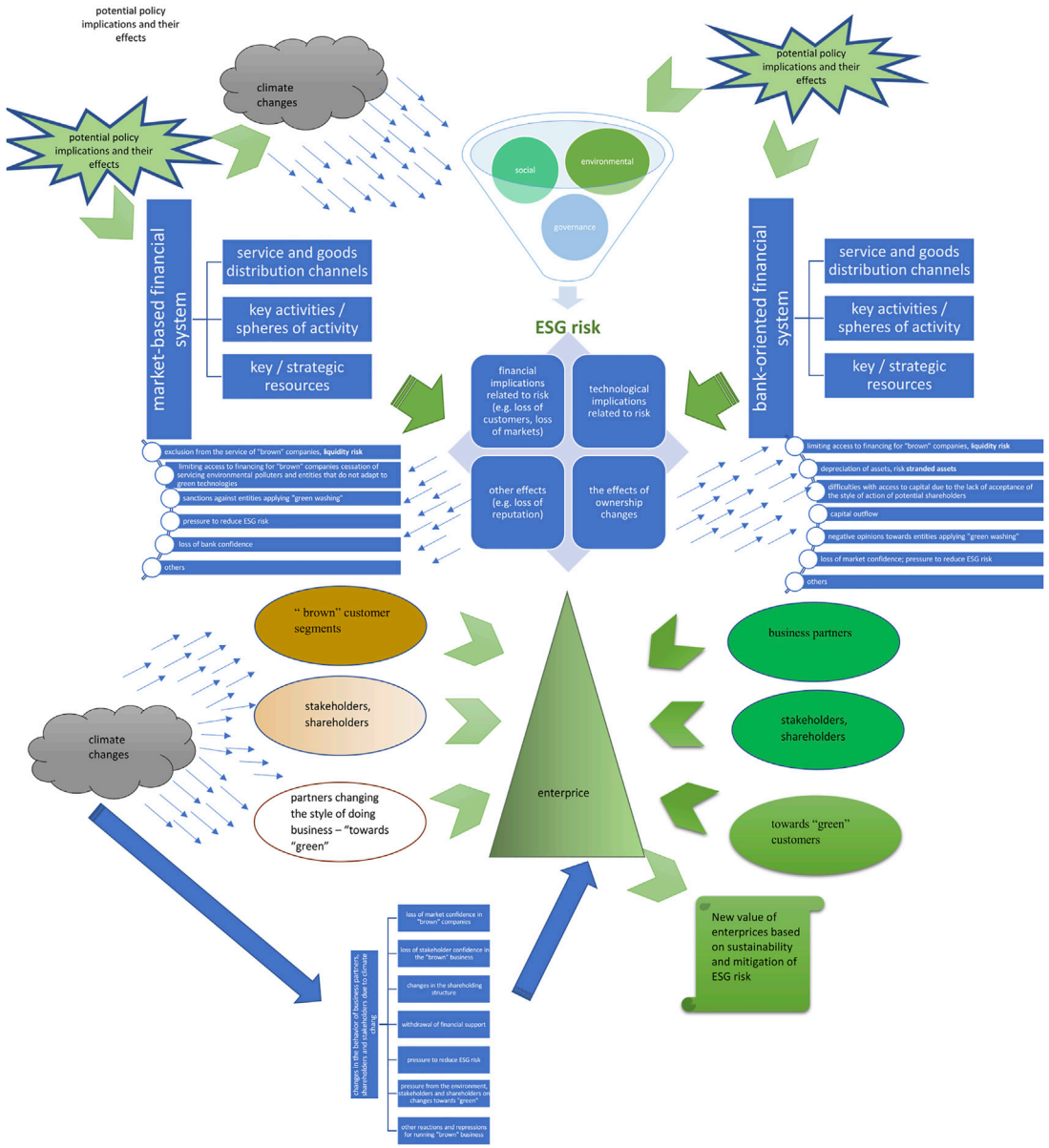

FIGURE 9
Relationship between ESG risk—bank based model and ESG risk—market based model, Source: own elaboration.

with the shift towards sustainability, he must not only redefine his business model, but also learn to manage risk. Financial institutions representing two financial systems (the market-based financial system as well as in the bank-oriented financial system) have extensive experience in risk management. It is through cooperation that they can transfer knowledge and methods of mitigating environmental risk or ESG to their clients. Collaboration is at the heart of qualitative changes related to environmental risk factors. The cooperation may imply changes both in the area of mentality and the perception of the importance of sustainability, as well as increase the sensitivity to ESG risk factors, social responsibility or the fulfillment of obligations resulting from the adopted SDG goals.

Previous research points to the importance of companies in creating green economic growth, circular economy, sustainability, as well as achieving SDG's goals. Our research shows the importance and role of the risk of non-financial factors. As well as the impact of ESG factors and the ESG risk itself on the development of cooperation between enterprises and financial institutions, including banks. ESG risk has now become the leading type of risk affecting the operating activities of business entities as well as being taken into account in the

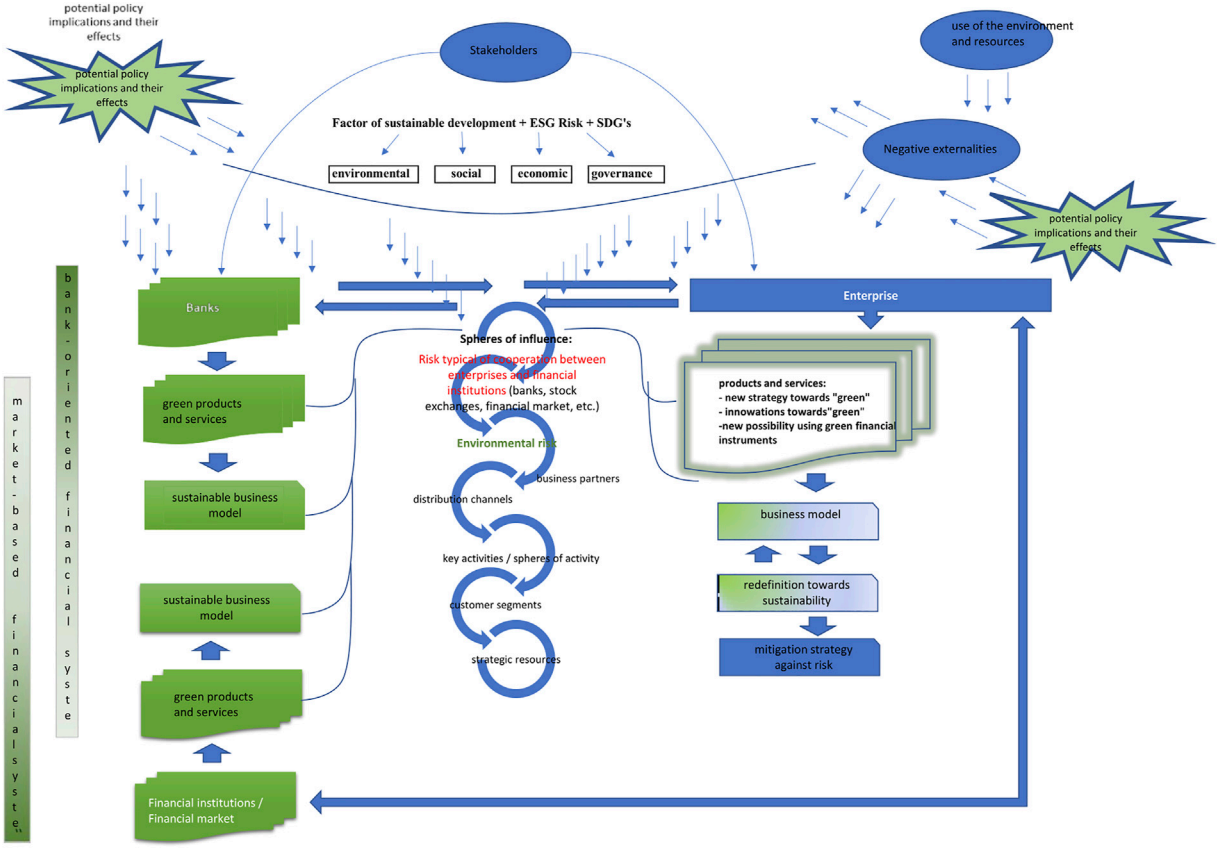

FIGURE 10
Mutual interactions between the financial institutions and the enterprise in terms cooperation towards sustainability, mitigation risk and change the business models, Source: own elaboration.

business models of financial institutions and banks. Extending the types of risks analyzed by banks and financial institutions to include non-financial issues, including ESG, becomes important, and in view of climate change, it becomes crucial. Risk considerations ESG also points to the need to ensure that companies fulfil their role in sustainability innovation so they can continue to be a major contributing factor in the economy. The impact on climate change with the use of innovations is widely known, but it should be pointed out that the implementation of climate and environmental goals requires both appropriate procedures and capital at the level appropriate to the needs. Thus, there is a cooperative relationship between banks' business models, sustainable financing, sustainable banking products and services supporting sustainability goals. To help companies accomplish this goal, financial institutions including banks should work to overcome the obstacles companies face in this regard, the companies main obstacle being access to and use of sources of finance, (Petersen and Rajan, 1994; Beck and Demirgüç-Kunt, 2006; Beck et al., 2008; Bruns and Fletcher, 2008; Wonglimpiyarat, 2015; Badaj and Radi, 2017; Shihadeh, et al., 2019). The interaction and even the creation of relations between global financial markets including banks and the economy influence sustainable development (Huang, 2011). For individual companies sustainability translates into corporate social responsibility, which is modelled in the direction of ESG risk reduction (Dahlsrud, 2008). Models of shaping the relations between enterprises and financial institutions, including banks, are more and more needed.

Therefore, it can be concluded that the strategy for the development of responsible business should therefore include patterns of cooperation between financial institutions, including banks and enterprises. These benchmarks should take into account: the economic (profit), ecological (planet) with ESG risk, social (people) dimensions, prosperity (economic, social and technological progress occurs in harmony with nature) and partnership. To ensure the indicated 5 "P", it is important for sustainability, circular economy and environmental to finance their implementation, that is, developing relations between entireties and financial institutions, including with banks.

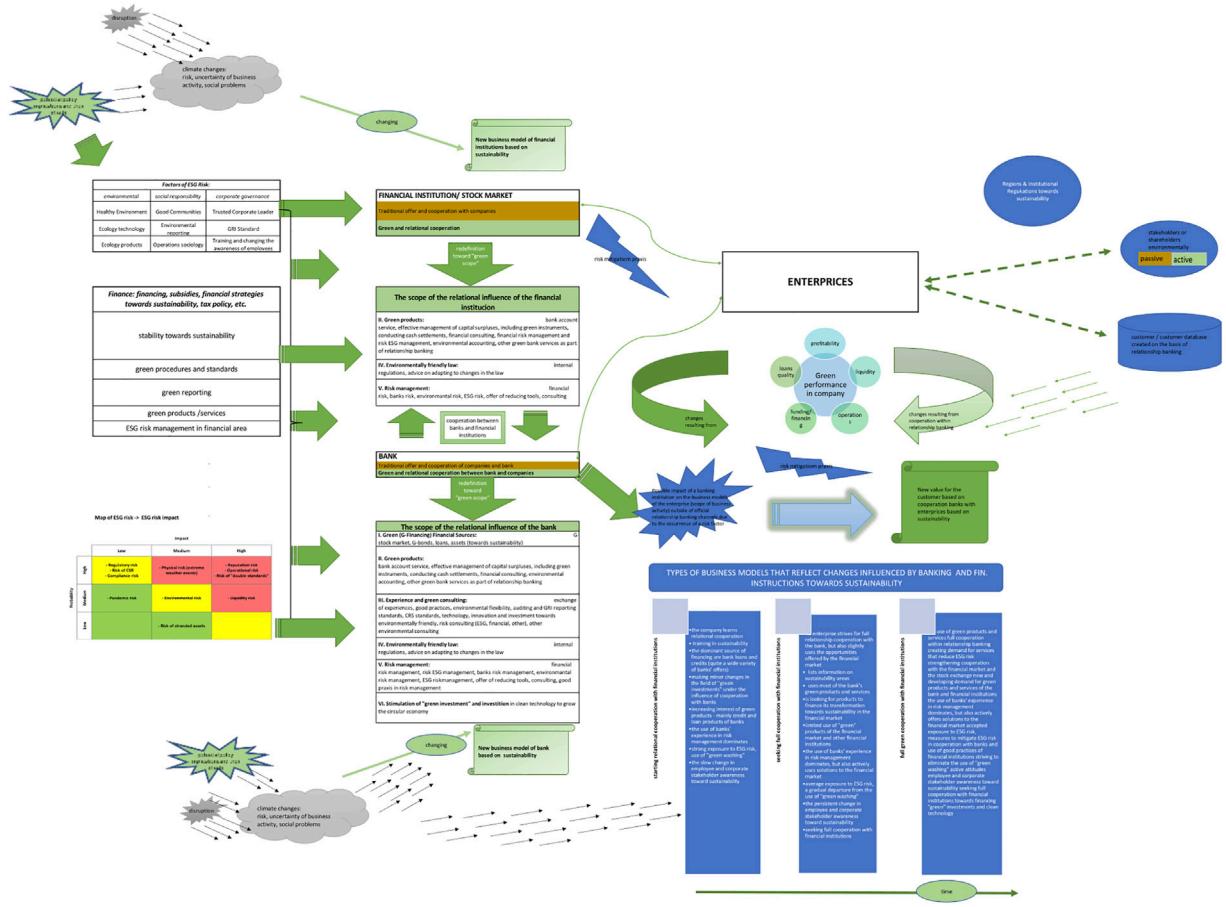

FIGURE 11
A proposed financial institution—enterprise cooperation model based on the bank-oriented financial system model, Source: own elaboration.

The literature on the subject also points to the special importance of the financial institution-client relational approach. The literature on the subject also indicates that these relations are shaped differently depending on the adopted basic models of the financial system were established - Anglo-Saxon model (market-based system) and the continental one (bank-oriented financial system). When building a model of cooperation for the financial institution-client, first of all the theoretical achievements in the field of shaping relations and cooperation should be taken into account. (Zioło et al., 2021) The relationship is based on two dimensions: time, which is the measure of the length of cooperation between the financial institution (important for risk assessment) and the companies (duration), and the scope of cooperation measured by the types of products and services used or wanted by the company (scope). At this point, it should be noted that ta cooperation may be of particular importance in developing a business based on sustainability and will also be of particular importance in reducing ESG risks for clients. One should look for strength in mutual relations and exchange of experience in the field of ESG risk mitigation, as well as a new value both for financial institutions, including banks, and for their clients (entireties, enterprises).

Figure 11 presents a proposed financial institution -enterprise cooperation model based on the bank-oriented financial system model, which takes into account the above assumptions. The scope towards "green" of the activities of banks towards "greening" is very wide and abounds in new products and services (full range). Financial institutions in this model have a limited scope towards "green".

Banks may operate directly or indirectly in the insurance, investment and other areas of the financial system. Banks can also freely acquire stocks and shares in non-financial enterprises. They can also cooperate with financial institutions, conclude agreements with them and offer their products. As a result, they often act as both shareholder and lender of enterprises. Thus, they can force business changes towards sustainability and the use of "green" products. Cooperating enterprises have the

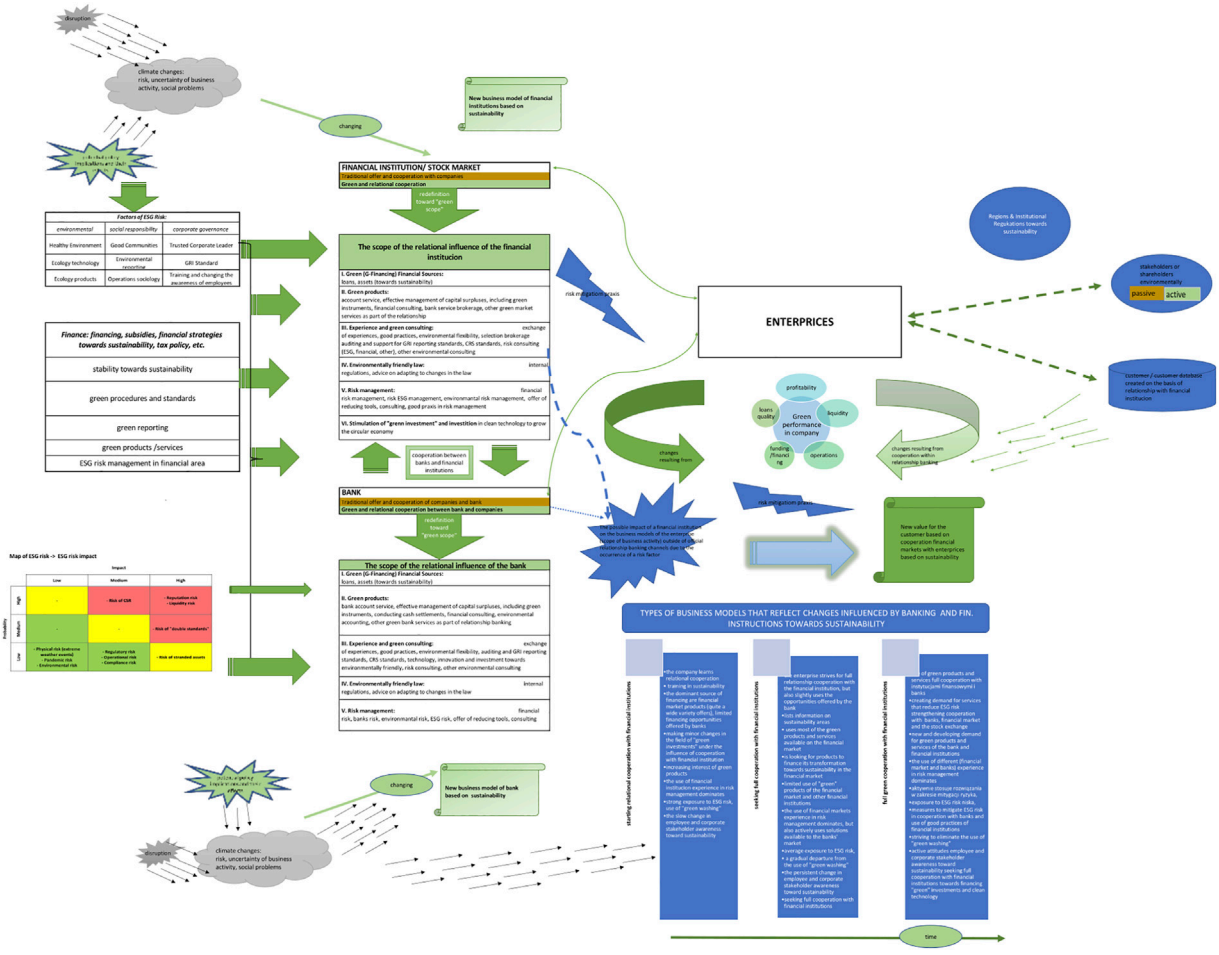

FIGURE 12
A proposed financial institution—enterprise cooperation model based on the market-based financial system model, Source: own elaboration.

opportunity to lower the financial risk, which favors the use of "green" products and changing their business models. The scope of "greening" depends on the time of cooperation, which translates into three model proposals for business models of enterprises. The problem of reducing non-financial risk and ESG risk is solved based on the use of the relationship with the bank. A specific problem that must be solved is "green washing". In this case, banks as dominant institutions influence the elimination of this phenomenon through business strategies, products and services as well as the applicable procedures. An important stakeholder in the elimination of green washing is the stakeholder and the customer. These two groups of entities also contribute to the reduction of ESG risk, in particular the reputational risk.

As shown in Figure 9, in the part showing the risk map, banks are an important institution supporting corporate risk mitigation. On the one hand, the experience of banks allows enterprises to use good practices within the framework of cooperation, but on the other hand, the banking procedures themselves force enterprises to behave responsibly.

Banks are the dominant institution in terms of influencing the changes towards sustainability that are taking place in enterprises. They also try to integrate their business models towards sustainable development with the financial market. Banks imply the greening of their clients' business models. Financial markets are not so active in creating "green" changes.

Figure 12 presents a proposed financial institution -enterprise cooperation model based on the market-based financial system model.

The scope towards "green" of the activities of financial institution towards "greening" is very wide and abounds in new products and services (full range). Clients use the basic banking offer (limited scope, usually "brown-passive"). Banks in this model have a limited scope towards "green". Investment banks become a separate institution, offering a new "green" quality of investment banking products towards sustainability. Financial institutions may operate

directly or indirectly in the insurance, investment and other areas of the financial system. Financial institutions can cooperate and influence banks towards "greening". The financial institution is becoming an institution creating new "green" products for customers and changing the approach to ESG risk factors. Banks change their offer under the influence of actions and pressure from financial institutions, just as insurers or entrepreneurs do. Financial markets influence not only changes in the scope of products, but also enforce ecological responsibility of the business. Offering finance for changes towards sustainability, they can force business changes towards "green" investment and the use of "green" products. Cooperating enterprises have the opportunity to lower the financial risk, which favors the use of "green" products and changing their business models. The scope of "greening" depends on the time of cooperation, which translates into three model proposals for business models of enterprises. The problem of reducing non-financial risk and ESG risk is solved based on the use of the relationship with the financial institution. Banks can use the rich experience of financial institutions in the field of risk management and mitigation. They can also learn naturally from "green" banks. A specific problem that must be solved is "green washing". In this case, financial institution (all because their reputation depends on it) influence the elimination of this phenomenon through business strategies, products and services as well as the applicable procedures. An important stakeholder in the elimination of green washing is the stakeholder and the customer. These two groups of entities also contribute to the reduction of ESG risk, in particular the reputational risk. As shown in Figure 10, in the part showing the risk map, financial institution and banks (cooperating and exchanging experience) are important institution supporting corporate risk mitigation.

Financial market institutions and the stock exchange are dominant institutions in terms of influencing changes in the direction of sustainability that are taking place in enterprises. They also try to integrate their business models towards sustainable development with the financial market. Financial institutions imply greening the business models of their clients—enterprises. Banks play a complementary role in this process and are not as active in creating "green" changes.

Analysis of cooperation models, a financial institution, an enterprise allows for the formulation of the following recommendations:

- Financial institutions should clearly communicate and strive to unify the approach in terms of ESG risk management procedures and expectations so that entrepreneurs are aware of the evaluation criteria and terms of cooperation with a financial institution and are treated on the same terms ensuring comparability of the approach of financial institutions;
- Financial institutions should apply a uniform system of restrictions on the approach to handling the so-called "dirty business", i.e., exclusion from service or increased cooperation costs as a risk premium;
- A register of greenwashing entrepreneurs should be established based on cases identified by financial institutions;
- ESG risk should be included in the customer segmentation in dynamic terms, allowing for monitoring changes in the customer-enterprise profile;
- A register of contractual clauses improving ESG risk management should be developed;
- Financial institutions should monitor the spread of green behavior among entrepreneurs and reach entrepreneurs with a sustainable product offer in the process of transforming business models towards sustainability in order to support them;
- Financial products and transaction collateral should be valued taking into account the ESG risk;
- Financial institutions should perform an advisory function in the field of transforming business models of enterprises towards sustainability.

Generally, we should also consider the two consequences of changes in business models in the context of our research. The appearance of political risk and the call to political risk. This translates into political implications on cooperation models between financial institutions and enterprises. The emergence of political risk, which can be understood as the execution of political power in a way that threatens a company's value (Bekaert et al., 2015). Under the influence of international regulations or the European Union, it will be necessary to adjust in all sectors. On the one hand, this will cause protests (as indicated by Bekefi and Epstein, 2006), as well as an increase in the cost of raising capital for the planned changes towards sustainability (Belkhir et al., 2017). Thus, the risk of ESG will increase, especially in the "S" area. The profitability of enterprises will change, and there will be strong pressure from stakeholders to limit the "new value" towards the "S" area of ESG factors. The political factor may cause shocks in the financial market (in the Anglo-Saxon model of banking systems) and affect the profitability and behavior of banks (in the German-Japanese model of banking systems). However, it should be remembered that the political factor will have an impact as described by Bekefi and Epstein. (2006) the political factor will then have an impact on cooperation models between financial institutions and enterprises if there is a simultaneous influence: (a) government policies towards business, or (b) the firm's current or future operations or value.

The literature on the subject highlights the influence of the political factor on green finance, green innovation and social globalization environmental quality (Kirikkaleli and Adebayo, 2022). This is an important element that manifests itself in the "G" risk factor of ESG and may create political risk. In addition, causality is indicated at various periods between political risk, green finance, green innovation, economic growth, social factors. This leads to the conclusion that the consideration of ESG factors serves as a reference point for governments and policymakers in

terms of creating interventionist instruments targeting the financial market and banks to redirect their business models towards investing in eco-friendly technologies in order to improve environmental quality.

6 Conclusion

The ESG risk affects the operations of enterprises and financial institutions. Both entrepreneurs and financial institutions adjust their business models towards sustainability. Adjustment measures taken by financial institutions in the field of sustainable business models influence enterprises' business models. This impact depends on the business sector and the financial system model. In the bank-oriented model, the role of banks as leading capital donors makes them crucial for entrepreneurs' decisions regarding the transformation of business models towards sustainability. When assessing the risk, financial institutions define financial conditions for enterprises - the more stringent, the higher the ESG risk. The reputation risk, which banks consider as a risk related to listed companies, plays an important role here. In the market-oriented model, the stakeholders are of crucial importance for ensuring sustainability and influencing enterprises. While in the case of the bank-oriented model, the ESG risk transmission channel is mitigated mainly by credit risk management and creditworthiness assessment procedures, in the market-oriented model, the stakeholders and disclosure of information about ESG activities by companies are crucial. The article is one of the first to include the financial system model in the ESG risk analysis in the context of sectoral enterprise analysis. The paper uses fuzzy cognitive maps and the correspondence analysis to diagnose which ESG factors affect enterprises to the greatest extent. The fuzzy cognitive maps analyze the importance of the social, environmental, and technological factors in building sustainable business models for enterprises from the service sector, industry, and agriculture as a specific form of economic activity. A general fuzzy cognitive map for business has been built and proved that the analyzed factors are significant in creating sustainable business models, creating a network of connections of a cause-and-effect nature. At the same time, it has been presented that negatively charged relations refer mainly to companies from the industry sector. As a result of the correspondence analysis, four typological groups of enterprises were distinguished. The first group included enterprises from the healthcare sector and from other sectors of business activities, which are characterized by highly sustainable business models built on social, organizational, and technological factors. What is essential, enterprises from this group cooperate with environmentally-friendly financial institutions. The second group includes enterprises from housing and non-material municipal services, construction, trade, and other sectors of non-material services; they put emphasis on the cooperation with the environment- and society-friendly financial institutions and build their business models, based mainly on social aspects as employee-friendly and digitized organizations. The third group of enterprises has been assessed as being below the average and, to an average extent, considering the social, organizational, and technological factors while cooperating with financial institutions. The last group of enterprises does not implement sustainable business models, nor does it cooperate with sustainable financial institutions. Enterprises that implement sustainable business models cooperate with sustainable financial institutions. It is because of the influence of impulses from the financial sector, expecting their partners to meet the sustainability requirements specified, among other things, in risk assessment procedures. The study confirms that there is an exchange of experiences and the knowledge transfer from the financial institution to the enterprise. Therefore, the business models of enterprises and financial institutions interpenetrate in terms of ensuring sustainability. Entrepreneurs who do not work with environmentally friendly financial institutions have been assessed as being below the average, and reduced their distance to the competition. The study has limitations due to the availability of comparable public research data. The future work will concern a separate analysis of ESG factors for the bank-based model and the market-oriented model depending on the seat of the financial institution, i.e., the study will include the spatial context.

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

MZ, BF, and IB contributed to conception and design of the study. IB and KC organized the database. IB and KC performed the statistical analysis. MZ, BF, and AS wrote the first draft of the manuscript. MZ, BF, AS, IB, and KC wrote sections of the manuscript. All authors contributed to manuscript revision, read, 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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Corporate digitalization, application modes, and green growth: Evidence from the innovation of Chinese listed companies

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Digitalization is one of the main ways for enterprise growth in the digital economy era. However, the existing literature on digital technology application models and their impact on corporate green growth is rare. By using the green innovation data of Chinese A-share listed companies from 2008 to 2020, this paper empirically investigates the association between enterprise digitalization and green innovation. The empirical results show that digitalization has significantly improved enterprises' substantive green innovation level, which is valid after conducting a series of endogenous and robustness tests. Further results show that digital technology application, intelligent manufacturing application, and modern information system application are the three main models of digitalization to promote green innovation of enterprises, while internet business model application cannot significantly promote corporate green innovation. In addition, the mechanism analysis results indicate that the increase in government subsidy and corporate own R&D investment contribute to the incentive effect mentioned above, while the loss of governance efficiency and fluctuation of the external environment offset this effect. This incentive effect is more obvious in non-state-owned, high-tech, and lower-polluted industry enterprises. Our paper reveals the mode and mechanisms for enterprises to realize innovative green growth by applying digital technology in the digital economy era, which is of great significance to relevant theoretical research and policy formulation.

KEYWORDS

corporate digitalization, digital technology application, intelligent manufacturing application, modern information system, internet business model application, corporate green innovation

1 Introduction

With the increasing development of the global economy, environmental pollution and ecological degradation have become common problems of human beings nowadays (Wang et al., 2020; Lin and Zhou, 2022). As green technology can improve the effective utilization of resources and reduce the pollution emission intensity in the production process (Li and Masui, 2019; Wang et al., 2020), it becomes an inevitable trend for economic and social development to support green development with technological progress (Karmaker et al., 2021; Li and Shen, 2021). However, the technical support for green development is seriously insufficient. Taking China as an example, its overall innovation level shows the characteristics of large quantity but poor quality, and the proportion of green innovation is relatively low. Due to the inherent

characteristics of green innovation, such as high investment, high risk, long return cycle, and a high degree of specialization, green innovation projects face problems of insufficient investment and financing constraints (Carrión-Flores and Innes, 2010; Berrone et al., 2013; Amore and Bennedsen, 2016).

With the global economy entering the digital era, the proportion of the digital economy in the economy is increasing yearly. On the one hand, the digital economy can improve the efficiency of resource allocation and reduce the pollution emissions from ineffective production; On the other hand, it can promote green innovation through integration with the real economy and become the key to solving environmental problems. However, the impact of corporate digital transformation on green innovation is poorly studied. This paper aims to analyze the impact of corporate digital transformation and its application models on corporate green innovation and the underlying mechanisms which may contribute to solving the research gap mentioned above.

From the research perspectives of micro and macro levels, there have been many studies on the innovation incentive effect of the digital economy. From the macro perspective, previous researchers have studied the mechanisms of the digital economy promoting industrial ecological integration and innovation, thus achieving the optimization and upgrading of industrial structure and high-quality economic development. For example, Estevez and Janowski (2013), Almeida and Zouain (2016), and Das and Das (2022) study the role of the digital economy in economic development from the perspectives of sustainable development goals, business environment, financial development, international trade, entrepreneurship, respectively. These studies show that digital technology provides opportunities for innovation and promotes the organic integration between green technology innovation and green economic growth.

From the micro perspective, scholars study how digital technology can reduce production factor costs and improve resource allocation efficiency, promote enterprise technology diffusion, increase innovation output and change management mode; Aaron and Jason (2016) point out that the knowledge spillover effect of the digital economy forced the reduction of manufacturing costs within the industrial system, and enhanced the link with the external environment, so as to achieve the goal of ecological environment governance and resource protection in the process of technological innovation. Thompson et al. (2013) argue that the increasingly innovative digital technology creates multidimensional scenarios, effectively reducing inefficiency and unnecessary resource loss. Goldfarb and Tucker. (2019) find that corporate digitalization can reduce information asymmetry by improving the share of enterprise information, which thus promotes corporate green technology innovation. Mubarak et al. (2021) insist that corporate digitalization can promote collaborative innovation and realize the integration and reconstruction of knowledge in different fields, thus encouraging corporate green innovation.

However, few studies explore the digital economy's green innovation performance from the application types of corporate digitalization. At the same time, the mechanisms behind the association between corporate digitalization and green innovation still need further analysis. This paper conducts an empirical study on the above issues using the financial data of Chinese listed companies from 2008 to 2020. By manually collecting the digital strategic keywords in the annual reports of listed companies to construct the corporate digitalization index, this paper can creatively divide their digital transformation into four types, i.e., digital technology application, intelligent manufacturing application, modern information system application, and internet business model application. Therefore, this paper can make an innovative empirical study on the impact of enterprise digital types on green innovation.

Our empirical results find that corporate digitalization can significantly improve substantive green innovation. We also conduct a series of endogenous and robustness tests, which further prove this conclusion is valid. Further results show that digital technology application, intelligent manufacturing application, and modern information system application are the three main models of digitalization to promote corporate green innovation, while internet business model application cannot. In addition, this paper finds that the incentive effect mentioned above is mainly realized by the increase of government subsidy and corporate own R&D investment, while offset by the loss of governance efficiency and fluctuation of the external environment. This incentive effect is more prominent in non-state-owned, high-tech, and lower-polluted industry enterprises.

This paper has at least three marginal contributions. First, based on the micro perspective, this paper studies the effect of green growth on enterprises under their digital transformation strategy, which deepens the understanding of the digital economy's low carbon value and green feedback efficiency and provides micro empirical evidence for its innovation incentive effect. Second, using the text recognition method, this paper innovatively constructs the enterprise digital transformation indices by identifying the digital keywords from the annual enterprise reports, which enriches the methodology and ideas for data acquisition of related research. Third, we innovatively classify the types of corporate digital transformation and study the heterogeneous effects of different digital applications to stimulate corporate innovation, further promoting the theoretical depth of digital economy research.

2 Theoretical analyses and research hypotheses

As the driving force of China's innovative development, the digital economy has become the key factor in promoting high-quality economic development. Digitalization is an inevitable choice for enterprises in the era of the digital economy and plays an important role in China's economic transformation and development. As a new form of innovation, green innovation can drive rapid economic growth and positively affect the ecological environment. Green innovation has gradually been attached to importance by more and more enterprises and has become an innovation path universally followed by countries worldwide in pursuit of sustainable development goals.

It is generally believed that the influencing factors of enterprise green innovation mainly include environmental regulation pull, government subsidy pull, market push, R&D investment pull, technology push, *etc.* (Chen et al., 2017; Li et al., 2018; Wang et al., 2019). Existing research has fully proved that the digital economy has achieved technological innovation with high efficiency, low cost, and less resource loss and has become a critical path to promoting high-quality development of green innovation. Corporate digitalization can improve the efficiency of resource allocation, reduce the pollution emissions of ineffective production, and promote green innovation

through integration with the real economy (Li and Shen, 2021; Liu et al., 2022). Corporate digitalization will enhance innovation efficiency and reduce innovation costs and become an important grabbing hand to solve environmental problems for substantial, sustainable development.

As an important starting point for China's high-quality economic development, the digital economy is the government's key focus. On the one hand, Corporate digitalization can help enterprises obtain more government subsidies and become an important driving force for enterprise development under the regulation of industrial policies and market mechanisms; Moreover, through digitalization, enterprises can optimize their innovative technology resources and increase their R&D investment (Schoenecker and Swanson, 2002), to further enhance their innovation capabilities (Subramaniam and Youndt, 2005), and thus affect their green technology innovation. On the other hand, in the process of digitalization, driven by the digital economy, the supervision, incentive, and decision-making of enterprises may be affected, thus affecting the governance efficiency of enterprises; In the wave of the digital economy, the risks and challenges brought by the new technology revolution will bring more uncertainty to the business environment of enterprises, which may affect the green innovation drive of enterprises. Therefore, this paper conducts empirical research on the relationship between corporate digitalization and green innovation from the micro level and makes research hypotheses from four aspects of resource allocation effect, R&D investment effect, corporate governance effect, and environmental fluctuation effect in mechanism analysis.

First, the digital economy improves the resource allocation effect through the enabling effect, thereby promoting green innovation of enterprises. Green innovation is a technological innovation output that comprehensively considers the environmental burden, uses new concepts and technologies, and reduces environmental pollution and raw materials and energy use. The gradual improvement of digital infrastructure has significantly promoted innovation frequency, technology diffusion, and production link optimization, thus promoting new value creation under low resource consumption conditions in the process of continuous construction and consolidation of green innovation infrastructure. The digital economy can also promote the coordinated development of economic activities, resources, and the environment. For enterprises, in the process of continuously improving the efficiency of resource allocation, the green growth of enterprises has stimulated the green innovation momentum of the digital economy. In addition, through digital construction, the digital economy can also improve the efficiency of resource integration and environmental monitoring capabilities, thus creating greater possibilities for green innovation of enterprises. For the government, the extent enterprises attach importance to green development directly determines whether they will carry out green innovation.

On the one hand, the government enables enterprises to achieve sustainable development through digitalization through industrial policies and optimizes the technological resources to carry out green innovation while enterprises undergo digitalization transformation. On the other hand, the government subsidizes enterprises in the region to carry out green innovation, and the incentive effect generated by the development of green technological innovation for enterprises also urges enterprises to carry out green innovation. Based on this, this paper proposes the first research hypothesis.

H1. Corporate digitalization will help enterprises obtain government subsidies to better support enterprises to carry out green technology innovation.

Second, the digital economy can improve enterprises' investment in green R&D projects by expanding their green innovation boundaries and improving their financing availability. Green innovation projects have the common characteristics of innovation projects, i.e., high investment, high risk, and long return period. In addition, enterprises are under strategic consideration and generally do not want to disclose too many details of R&D projects. Green innovation shows a large information asymmetry. Therefore, enterprises face the inherent problem of insufficient investment in green innovation. The digital economy can promote green innovation of enterprises by improving innovation efficiency and reducing the level of information asymmetry.

On the one hand, the digital economy opens up new development paths and feasible space for effective breakthroughs in innovation activities. The gradual improvement of digital infrastructure has significantly promoted innovation efficiency (Kohli and Melville, 2019). The knowledge spillover effect of the digital economy forced the optimization and reduction of manufacturing costs within the industrial system and enhanced the linkage and response-ability with the external environment to achieve the goal of ecological environment governance and resource protection in the process of technological innovation (Aaron and Jason, 2016).

On the other hand, enterprise digitalization can accelerate the delivery and feedback of information in the organizational structure, promote the sharing of information related to the internal and external environment and resources of enterprises, and thus reduce the financing constraints of enterprises. Specifically, information sharing includes internal and external dimensions. Internal information sharing refers to the transmission and integration of information among different organizations within an enterprise, which promotes the enterprise to the integration of internal resources through the exchange and integration of information among various departments (Carr and Kaynak, 2007). External information sharing mainly focuses on the communication between enterprises and investors in the capital market, which will have an important impact on investors' investment decisions. Based on this, this paper proposes the second research hypothesis.

H2. Corporate digitalization helps enterprises increase R&D investment, thus improving enterprises' green innovation level.

Third, the digital technology behind the digital economy can be applied to the corporate governance mechanism, which is conducive to green innovation activities in which enterprises can invest to obtain long-term value. The rapid development of the digital economy not only brings great changes to the traditional industrial model and production mode but also leads to a new round of industrial reform; It also brings great changes to the corporate governance structure and governance model. The boundary between various departments is gradually weakening, leading to the concept change of corporate governance. In the process of digitalization, enterprises may bring about the conflict between the disruptive innovation of production and operation mode and the untimely change of management and governance concept, which reduces the innovation activities of

enterprises, including green technology, in the process of enterprise adaptation and adjustment. Digital manufacturing can realize good management of the whole life cycle of products. Through the use of data technology and platform, product manufacturing, design and development, process flow, and resource utilization can be transparently managed, which is conducive to solving the principal-agent problem, thus improving the willingness of management to invest in green innovation projects. However, despite this, the application of digital technology may break the management mode and generation mode based on the original technology, thus causing a loss of governance efficiency in the short term. Therefore, the governance effect behind the digital economy and green innovation of enterprises remains to be tested. Based on this, this paper proposes the third research hypothesis.

H3. Corporate digitalization may promote enterprises' green innovation by improving corporate governance.

Fourth, the digital economy may also cause short-term fluctuations in the external environment of enterprises, which is not conducive to their green innovation activities. On the one hand, driven by new development concepts and sustainable development goals, green technology innovation in traditional industries will enhance their competitiveness in the market and become an inevitable choice for enterprises to make digitalization with the continuous improvement of environmental regulations and production environmental protection standards. On the other hand, the digital economy is updating too fast. In continuous upgrading, relevant policies and regulations are imperfect, and new risks will follow. In addition, due to the network effect and winner take all effect, enterprises' uncertainty in the digitalization process is also greatly increased, and green technology innovation is stagnant without corresponding protection. Based on this, this paper proposes the fourth research hypothesis.

H4. Corporate digitalization may increase enterprises' environmental fluctuations, thus affecting enterprises' green innovation.

3 Data description and methodology

3.1 Data sources

Our study sample comprises Chinese A-share companies listed on the Shanghai Stock Exchange and Shenzhen Stock Exchange from 2008 through 2020. We obtain data from at least three primary sources: The China Stock Market and Accounting Research (CSMAR) database, the WIND database, and companies' financial reports. We drop all financial listed companies, special treatment (S.T.) firms, particular transfer (P.T.) companies, and firms with missing relevant data. We winsorized all continuous variables at 1% at both tails.

3.2 Variable description

3.2.1 Corporates' green innovation

This study uses green patent applications as a proxy measure of corporate eco-innovation output. In China, patents are classified into three classes: invention patents, design patents, and utility model patents. Of the three patent classes, invention patents symbolize quality innovation (Tan et al., 2020). Therefore, in addition to using the total number of green patent applications to measure the quantity of green innovation, we also use the number of green invention patent applications to measure the quality of green inventions. We collect our patent data from the CSMAR database. We use the natural logarithm of one plus the number of green patent applications to reduce skewness bias (Wang et al., 2020).

3.2.2 Digitalization

Corporate digitalization, as our explanatory variable, is measured by the frequency of digital-related keywords that appear in corporate annual reports. Since The enterprise annual report can usually express the company's operation status and development path (Donovan et al., 2021), we assume the annual report can also tell us about the development of corporate digitalization. We use python to calculate the frequency of digital-related keywords in the annual reports of listed companies and use it to evaluate the implementation of enterprise digital transformation. Keywords that we collected include data, digital, internet, smart, intelligent, integrated, virtual, automatic, precise, online, networking, and portable. We denote the results as *DIG*.

3.3 Models

We use the baseline OLS estimation model in our estimations following prior literature. The following basic model is used:

$$\ln GTP_{i,t} = \alpha_0 + \alpha_1 \times \ln DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \quad (1)$$

$$\ln GIP_{i,t} = \alpha_0 + \alpha_1 \times \ln DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \quad (2)$$

Where $\ln GTP$ and $\ln GIP$ represents the natural logarithm of one plus the number of total patents and the natural logarithm of one plus the number of patent inventions, while *DIG* represents measures of enterprise digitalization. *Controls* represents control variables, including *Firm Age*, *Firm Size*, *Leverage*, *SOE*, *ROA*, *Shareholder Size*, *Duality*, *Top Shareholder,* and *Top Ten Shareholders, Staff Size*. This study also controls for year fixed effects (γ_t), firm fixed effects (θ_c), and industry fixed effects (μ_h). Table 1 presents the detailed definitions and construction of the variables.

3.4 Descriptive statistics

We measure the different degrees of corporate digitalization using a dummy variable *D1_DIG*, which equals one if the firm has mentioned at least one digital-related keyword in its annual report and zero otherwise. From Table 2, we can see that the percentage of corporate digitalization increased from 88% in 2008% to 98% in 2020, while the mean value also increased from 25.18 to 130.23. It indicates a vast increase in digitalized enterprises and a decrease in non-digitalized enterprises.

Table 3 reports descriptive statistics for variables. The average value of green invention patents is 0.712, and the average value of total green patents is 0.393, showing that the high-quality green innovation

TABLE 1 Variable definitions.

Variables	Definitions
Panel A: Patent variables	
GTP	The number of firm *i*'s total green patent applications, including invention green patent applications, and utility model patent applications
GIP	The number of firm *i*'s invention green patent applications
lnGTP	The natural logarithm of one plus firm *i*'s total green patent applications
lnGIP	The natural logarithm of one plus firm *i*'s invention green patents applications
Panel B: Digitalization variables	
DIG	The frequency of digital-related keywords in corporate annual reports
D1_DIG	A dummy variable which equals 1 if firm *i* has mentioned at least one digital-related keyword in annual report in year *t* and 0 otherwise
D2_DIG	A dummy variable which equals 1 if DIG is greater than the median of sample in year *t* and 0 otherwise
Panel C: Other variables	
Firm Age	Firm *i*'s age, which equals to the difference of fiscal year *t* minus the year the firm was established
Firm Size	The natural logarithm of the book value of total assets
Leverage	The book value of total debts divided by the book value of total assets
Staff Size	The natural logarithm of staff size of firm *i* in year *t*
SOE	A dummy variable which equals 1 if firm *i* is a state-owned entity and 0 otherwise
ROA	Return on assets, which equals net income divided by total assets
Shareholder Size	The natural logarithm of shareholders of firm *i* in year *t*
Duality	A dummy variable which equals 1 if CEO and chairman is the same person and 0 otherwise
Top Shareholder	The percentage of shares owned by the largest shareholder in year *t*
Top Ten Shareholders	The percentage of shares owned by the largest 10 shareholders in year *t*
Fixed-phone	The natural logarithm of fixed phone users in 1985
RDexp	The natural logarithm of R&D expenditures
Subsidy	The natural logarithm of total subsidies from government
CG	Corporate government index, which is calculated by combining multiple indicators using principal component analysis
EF	Environmental fluctuation index, which is calculated by removing the industry influence with a series of methods after the residual value is calculated with the least square method

TABLE 2 Sample distribution.

Year	Total	D1_DIG = 1	D1_DIG = 0	Percentage	Mean of D1_DIG
2008	1324	1177	147	0.889	25.186
2009	1459	1339	120	0.918	29.183
2010	1792	1697	95	0.947	32.768
2011	2009	1938	71	0.965	38.272
2012	2128	2086	41	0.980	40.827
2013	2169	2108	61	0.972	45.363
2014	2285	2259	26	0.989	53.621
2015	2466	2447	19	0.992	67.955
2016	2744	2726	18	0.993	84.271
2017	3112	3078	33	0.989	98.649
2018	3195	3184	11	0.997	108.089
2019	3391	3358	32	0.990	121.443
2020	3840	3792	48	0.988	130.234
Total	31914	31189	725	0.977	77.794

TABLE 3 Descriptive statistics.

Variables	N	Mean	Std.Dev	Min	Max
Panel A: Patent variables					
GTP	31,914	0.712	2.840	0.000	21.000
GIP	31,914	0.393	1.629	0.000	12.000
LnGTP	31,914	0.202	0.585	0.000	3.091
LnGIP	31,914	0.141	0.456	0.000	2.565
Panel B: Digital transformation index variables					
DIG	31,824	77.794	116.330	0.000	1,713.000
LnDIG	31,824	3.746	1.120	0.000	7.447
Panel C: Other variables					
Firm Size	31,912	21.993	1.284	19.341	25.933
Firm Age	31,049	2.734	0.428	0.000	4.127
Duality	31,463	0.279	0.449	0.000	1.000
Shareholder size	31,894	10.232	1.219	3.178	12.787
Staff Size	31,877	7.613	1.274	4.111	11.096
Top Shareholder	31,900	34.833	14.997	8.770	74.980
Top Ten Shareholder	31,900	59.434	15.860	22.910	96.050
ROA	31,912	0.039	0.067	−0.298	0.214
SOE	31,900	0.374	0.484	0.000	1.000
Leverage	31,912	0.420	0.211	0.049	0.979

of sample companies generally accounts for about half of the total innovation. The standard deviations of *GTP* and *GIP* are more significant than the mean value, indicating that sample companies' level of high-quality green innovation varies greatly. The maximum value of *DIG* is 1713, and the average value is 77.79, indicating that the sample company's *DIG* is relatively low. In addition, the standard deviation of *DIG* is higher than the average value, indicating that the *DIG* of different companies varies greatly. The minimum value of Leverage is 0.049, and the maximum value is 0.979, indicating that the sample companies have significant differences in financial leverage. In addition, the mean value of *SOE* is 0, indicating that most sample corporates are non-state-owned enterprises.

Table 4 presents univariate statistics of the average difference between digitalized and non-digitalized companies. The univariate tests show that the digitalized firms have more green patent applications than the others. Therefore, digitalized companies are more innovative than non-digitalized competitors. Table 4 also shows that digitalized companies are more profitable, less streamlined, and have fewer employees. We also observed that private enterprises are more likely to be digitalized than state-owned enterprises.

4 Baseline results and mechanisms

4.1 Baseline results

Table 5 reports our baseline results controlling the year fixed effects, firm fixed effects, and industry fixed effects. Columns 1) and 2) show the regression results without control variables, and columns 3) and 4) show the regression results with control variables. Column (3) (4) shows that after adding the control variables into the regression, the coefficients on our explanatory variables DIG to the quantity and the quality of eco-innovation is 0.014 and 0.013, respectively. Both coefficients are positive and significant at a 1% statistical level in columns 1) and 2) and a 5% statistical level in columns 3) and 4). The results show that corporate digitalization could enhance both the quality and quantity of green innovation.

In addition, referring to the previous research, we also do a series of robustness tests to exclude other possible explanations including: 1) considering count dependent variables (Cameron and Trivedi, 2005; Yuan et al., 2015; Zhou and Zhang, 2016); 2) considering different

TABLE 4 Univariate analysis.

Variables	D1_DIG = 0		D1_DIG = 1		Differences
	Obs	Mean	Obs	Mean	T value
LnGTP	725	0.096	31189	0.142	−0.045***
LnGIP	725	0.143	31189	0.203	−0.060***
LnDIG	725	0.000	31099	3.833	−3.833***
Firm Size	725	22.01	31187	21.99	0.014
Firm Age	717	2.673	30332	2.735	−0.063***
Duality	715	0.225	30748	0.280	−0.055***
Shareholder size	725	10.55	31169	10.22	0.327***
Staff Size	725	7.876	31152	7.607	0.269***
Top Shareholder	725	34.16	31175	34.85	−0.688
Top Ten Shareholder	725	54.71	31175	59.54	−4.833***
ROA	725	0.036	31187	0.039	−0.004
SOE	725	0.570	31175	0.369	0.200***
Leverage	725	0.476	31187	0.419	0.057***

The T values for mean differences are based on t-tests. *, ** and *** denotes significance at the 10%, 5% and 1% level (two-tailed), respectively.

TABLE 5 Baseline result.

Variables	(1) lnGTP	(2) lnGIP	(3) LnGTP	(4) lnGIP
L.lnDIG	0.015***	0.014***	0.013**	0.012**
	(0.006)	(0.005)	(0.006)	(0.005)
L. Firm Size			0.013	0.007
			(0.010)	(0.008)
L.Firm Age			0.026	0.026
			(0.027)	(0.022)
L.Duality			0.007	0.005
			(0.011)	(0.009)
L.Shareholder Size			0.005	0.007
			(0.006)	(0.005)
L.Staff Size			0.012	0.012*
			(0.008)	(0.006)
L.Top Shareholder			−0.001*	−0.001
			(0.001)	(0.001)
LTop Ten Shareholder			−0.000	−0.000
			(0.001)	(0.000)
L.ROA			0.172***	0.141***
			(0.055)	(0.043)
L.SOE			0.026	0.025
			(0.028)	(0.023)
L.Leverage			0.057*	0.045*
			(0.032)	(0.025)
Constant	0.166***	0.105***	−0.509***	−0.390***
	(0.021)	(0.017)	(0.187)	(0.147)
Observations	27,059	27,059	26,658	26,658
R^2	0.561	0.547	0.108	0.083
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

time trends; 3) considering city-time fixed effects and industry-time fixed effects. Table 6 report the corresponding results. All robustness results support our conclusions.

4.2 Endogeneity

The above findings indicate a positive relationship between corporate digitalization and corporate eco-innovation. However, the results can be spurious due to confounding endogeneity bias. The main endogeneity concerns are reverse causality and omitted variable bias. We address the potential endogeneity issues using various econometric techniques, including the Heckman two-step model and instrumental variable IV) method.

4.2.1 Heckman two-stage method

The relationship between digital transformation and corporate eco-innovation may be endogenous due to sample selection bias and reverse causality. On the one hand, digitalization could promote eco-innovation. On the other hand, firms that actively engage in green R&D may also take various digital transformation initiatives to enhance eco-innovation, leading to biased and unreliable estimation results.

We employ the Heckman two-stage correction model to control for any self-selection bias in our sample firms. We use the dummy variable

TABLE 6 Considering count dependent variables.

Panel A The Poisson regression results.		
Variables	(1)	(2)
	GTP	GIP
L.lnDIG	0.160***	0.250***
	(0.007)	(0.009)
Control variables	YES	YES
Observations	27,304	27,304
Year fixed effects	YES	YES
Firm fixed effects	YES	YES
Industry fixed effects	YES	YES
Panel B The negative binomial regression results		
Variables	(1)	(2)
	GTP	GIP
L.lnDIG	0.066***	0.068***
	(0.024)	(0.024)
Control variables	YES	YES
Observations	11,323	9,671
Year fixed effects	YES	YES
Firm fixed effects	YES	YES
Industry fixed effects	YES	YES

Panel C Controlling different time trend terms				
Variables	(1)	(2)	(3)	(4)
lnGTP	LnGIP	LnGTP	LnGIP	
L.lnDIG	0.013**	0.012**	0.013**	0.012**
	(0.006)	(0.005)	(0.006)	(0.005)
City-time trend term	−0.000	−0.000		
Firm-time trend term	(0.000)	(0.000)	−0.000	−0.000
			(0.001)	(0.001)
Control variables	YES	YES	YES	YES
Observations	26,658	26,658	26,658	26,658
R^2	0.108	0.083	0.108	0.083
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES

Panel D Considering city-year fixed effects and industry-year fixed effects				
Variables	(1)	(2)	(3)	(4)
LnGTP	lnGIP	lnGTP	lnGIP	
L.lnDIG	0.014**	0.013**	0.013**	0.012**
	(0.007)	(0.006)	(0.006)	(0.005)
Control variables	YES	YES	YES	YES
Observations	24,529	24,529	26,564	26,564
R^2	0.615	0.602	0.604	0.586
City-Year fixed effects	YES	YES		
Industry-Year fixed effects			YES	YES
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 7 Heckman two-stage analysis.

	(1)	(2)	(3)
VARIABLES	Du_DIG	lnGTP	lnGIP
meanDu_DIG	4.454***		
L.lnDIG	(−0.212)	0.013**	0.012**
		(−0.006)	(−0.005)
Inverse Mills ratio		−0.027***	−0.013*
		(−0.01)	(−0.008)
Constant	−4.658***	−0.484**	−0.378**
	(−0.959)	(−0.189)	(−0.148)
Observations	26,618	26,584	26,584
R^2		0.109	0.083
Number of firms	3,238	3,237	3,237
Year fixed effects	YES	YES	YES
Firm fixed effects	YES	YES	YES
Industry fixed effects	YES	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

D2_DIG to measure companies with different degrees of digitalization. If *DIG* is greater than the median of the total sample, the dummy variable is equal to 1, which means that the company has undergone digital transformation. Otherwise, it is zero. We then use the digital mean value of other enterprises in the same industry as an exogenous variable (*meanDu_DIG*) in the Probit model. We estimate the *Inverse Mills ratio* in the first stage and add it to our regressors in the second stage estimations. Regarding the second stage results in Table 7, columns 2) and 3), all columns' coefficients for the *Inverse Mills ratio* are significant, suggesting that the sample had some selection issues. The second-stage regression results shown in columns 1) and 2) are significant at the statistical level of 5%, indicating the regression results are still significant after considering endogenous problems such as selection errors.

4.2.2 Instrumental variable estimation

To reduce the endogeneity effect of reverse causality between digital transformation and corporate green innovation, we adopt the instrumental variable IV) approach (two-stage least squares regression

TABLE 8 Instrumental variable method.

Variables	First stage	Second stage	
	(1)	(2)	(3)
	L.lnDIG	lnGTP	lnGIP
L.lnDIG		0.856***	0.610***
Fixed-phone	0 .023***	(0.288)	(0.216)
	(0.006)		
F statistics	15.250***		
A-can LM test		17.676***	17.676***
Control variables	YES	YES	YES
Observations	22,906	22,906	22,906
R^2		−1.247	−0.9810
Year fixed effects	YES	YES	YES
Firm fixed effects	YES	YES	YES
Industry fixed effects	YES	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

method) to deal with endogeneity bias between corporate digitalization and eco-innovation. We use each region's historical fixed telephone usage in 1985 as an instrumental variable (*Fixed-phone*) referring to Huang et al. (2019). The infrastructure required for using the fixed telephone is crucial to developing modern digital technology. Therefore, the popularization of fixed telephones can affect the digitalization of local enterprises. However, the use of fixed phones in the past has little to do with the green innovation of enterprises. The number of fixed telephone subscribers is cross-sectional data, which cannot be directly used for the metrological analysis of panel data. Referring to Nunn and Qian (2014), we multiply the number of firm R&D expenditures with a 2-year lag by the number of fixed telephone users in each province in 1985 to construct the interaction terms and use them as an instrumental variable for firm digitization.

We present the first and the second stage results in Table 8. The coefficient of corporate digitalization in the first stage is significant, satisfying the correlation hypothesis between the explanatory and the instrumental variables. The coefficient of corporate digitalization on green innovation is also significant in the second stage. The results support that corporate digitalization is positively related to green innovation of enterprises. In addition, the first-stage F-statistic value is greater than 10, indicating no weak instrumental variable problem. The A-can LM test result is more significant than ten, showing no unidentifiable problem and proving the validity of the instrumental variable selection. Overall, the baseline regression results still hold after considering the possible endogeneity problem in the model.

4.3 Mechanism analyses

Below we explore the possible mechanisms underlying the effect of digitalization on green innovation. We propose four mechanisms: resource allocation effect, R&D investment effect, corporate governance effect, and environmental fluctuation effect.

Following the approach of Heckman, Pinto, and Savelyev (2013) and Gelbach (2016), we first estimate the effect of digitalization on eco-innovation using Eq. 3, Eq. 4, then we evaluate the effect of digitalization on mechanism variables using Eqs. 5—8, and finally we estimate the effect of digitalization and mechanism variables on green innovation using Eq. 9, Eq. 10. The equations are listed below:

$$GTP_{i,t} = \alpha_0 + \alpha_1 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{3}$$

$$GIP_{i,t} = \alpha_0 + \alpha_1 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{4}$$

$$Subsidy_{i,t} = \alpha_0 + \sigma_1 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{5}$$

$$RDexp_{i,t-1} = \alpha_0 + \sigma_2 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{6}$$

$$CG_{i,t-1} = \alpha_0 + \sigma_3 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{7}$$

$$EU_{i,t-1} = \alpha_0 + \sigma_4 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{8}$$

$$GTP_{i,t} = \alpha_0 + \varphi_1 Subsidy_{i,t} + \varphi_2 RDexp_{i,t-1} + \varphi_3 CG_{i,t-1} + \varphi_4 EF_{i,t-1} + \alpha_1 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{9}$$

$$GTP_{i,t} = \alpha_0 + \varphi_1 Subsidy_{i,t} + \varphi_2 RDexp_{i,t-1} + \varphi_3 CG_{i,t-1} + \varphi_4 EF_{i,t-1} + \alpha_1 \times DIG_{i,t-1} + \boldsymbol{\beta} \times Controls_{i,t-1} + \gamma_t + \theta_c + \mu_h + \varepsilon_{i,t} \tag{10}$$

Where , $RDexp$, CG and EF denote mechanism variables for resource allocation effect, R&D investment effect, corporate governance effect, and environmental fluctuation effect; other variables and coefficients are set consistent with the baseline

TABLE 9 Mechanisms.

Panel A: First step		
VARIABLES	(1)	(2)
	lnGTP	lnGIP
L.lnDIG	0.013*	0.012***
	(0.006)	(0.005)
Control variables	YES	YES
Observations	26,658	26,658
R^2	0.108	0.083
Year fixed effects	YES	YES
Firm fixed effects	YES	YES
Industry fixed effects	YES	YES

Panel B: Second step				
VARIABLES	(1)	(2)	(3)	(4)
	LnSubsity	L.lnRDexp	L.CG	L.EF
L.lnDIG	0.055***	0.263***	−0.013**	0.021**
	(0.014)	(0.078)	(0.006)	(0.010)
Control variables	YES	YES	YES	YES
Observations	25,670	26,464	24,622	18,266
R^2	0.284	0.365	0.320	0.066
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES

Panel C: Third step		
VARIABLES	(1)	(2)
	lnGTP	LnGIP
LnSubsidy	0.011***	0.008**
	(0.004)	(0.003)
L. RDexp	0.004***	0.003***
	(0.001)	(0.001)
L.CG	−0.001	−0.003
	(0.012)	(0.010)
L.EF	−0.012*	−0.007
	(0.007)	(0.006)
L. DIG	0.001	0.002
	(0.007)	(0.006)
Control variables	YES	YES
Observations	14,181	14,181
R^2	0.095	0.072
Year fixed effects	YES	YES
Firm fixed effects	YES	YES
Industry fixed effects	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

regression. In the following, we separately analyze the mechanism of the results shown in Table 9.

4.3.1 Resource allocation effect

To identify how corporate digitization contributes to green innovation, we first examine whether they receive higher subsidies from higher levels of digitalization. If firms could receive more subsidies, we expect them to invest more in green innovation projects. We use government subsidies to firms to examine whether subsidies are associated with corporate green innovation.

The results in Table 9, Panel B, show that the coefficient on total subsidies received by firms is positive and statistically significant at the 1% level. It indicates that firm digitization increases innovation productivity by increasing government subsidies. Next, we control for other mechanism variables in the model and repeat the estimation. The results in Panel C of Table 9 show that the coefficient on subsidy revenue (0.011) is positive and significant at the 1% level. These findings suggest that green innovation output increases with subsidy revenue and reasonably suggest that subsidy revenue is a possible channel through which firm digitization promotes green innovation output.

4.3.2 R&D investment effect

We then examine whether corporate digitalization enhances R&D expenditures. If corporate digitalization improves the ability to integrate information and managers could use resources more wisely, we expect them to invest more in green innovation. We use firm R&D expenditures to examine whether R&D expenditures are related to green innovation.

The results in Table 10 Panel B show that the coefficient on R&D expenditure is positive and statistically significant at the 1% level. Next, we control for digitization and other mechanical variables in the model and repeat the estimation. The results in Panel C of Table 10 show that the coefficient on R&D expenditure (0.004, 0.003) is positive and significant at the 1% level. These findings show that R&D expenditures increase with digitization and suggest that R&D expenditures contribute to innovation efficiency.

4.3.3 Corporate governance effect

To study this mechanism, we construct an index of corporate governance efficiency in terms of supervision, incentives, and decision-making using principal component analysis. Specifically, we first used executives' remuneration and shareholding ratios to indicate the incentive mechanism of corporate governance. Secondly, we use the proportion of independent directors and the size of the board of directors to indicate the supervisory role of the board of directors. Thirdly, we use the proportion of institutional shareholding and the degree of equity balances (i.e., from the second to the fifth largest shareholder to the shareholding of the first largest shareholder) to indicate the supervisory role of the equity structure. Finally, we use duality to indicate the decision-making channel. We use principal component analysis to analyze corporate governance efficiency based on the above seven indicators. The first principal component in the principal component analysis reflects the comprehensive corporate governance indicators.

Panel B in Table 9 tests the impact of our enterprise's digitization on corporate governance. The results indicate a negative correlation between digitalization and the efficiency of corporate governance, and the coefficient is significant at the 1% level. The results indicate that more digitized firms instead reduce corporate governance. We then add other mechanism variables into the regressions and control for *DIG* to examine whether corporate green innovation can be promoted by increasing corporate governance. The results in Panel C show that all coefficients of corporate governance are small and insignificant, indicating that corporate governance has little effect on corporate green innovation. In general, corporate digitalization helps to reduce the cost of supervision in innovation activities. However, our regressions show that digitalization reduces corporate governance in the short term. Possible reasons may be the potential security risks behind digitalization and the time cost for executives to learn new technology. Corporate executives may be concerned about the leakage of personal information, which leads to less efficient management. Also, it takes time for corporates to apply digital technologies to corporate management, therefore corporate digitization may negatively impact corporate governance in the short term (Grove et al., 2018; Sama et al., 2022).

4.3.4 Environmental fluctuation effect

Finally, we study whether digitalization can reduce innovation R&D by improving the uncertainty of the operating environment. The market environment often affects the results of green innovation (Leonidou et al., 2017). The uncertainty of the market environment will bring uncertainty about the effect of green innovation (Ogbeibu et al., 2020). To measure the uncertainty of the market environment, we used the following three steps to measure: 1) Use the company's revenue data, set them every 5 years, and do the least squares regression. The residual is denoted as the fluctuation of marketing revenue, and the coefficient multiplied by marketing revenue is denoted as the regular marketing revenue. 2) Divide the standard deviation of marketing revenue fluctuation by the regular marketing revenue and calculate the average. 3) Divide the result of the second step by the median marketing revenue of all companies in the same industry in the same year to eliminate the industry's impact. We take the final calculated results as an index to measure the fluctuation degree of the business environment.

We first test the relationship between firm digitization and environmental uncertainty. The results in column 4) of Panel B of Table 9 show that the coefficient on environmental fluctuation is significantly negative at the 1% level. After observing the negative relationship between environmental uncertainty and R&D subsidies, we examine whether environmental fluctuation affects firms' green innovation. The results in Table 10 show that the coefficient of environmental fluctuation remains significantly negative in column 1) but insignificant in column 2) after including environmental fluctuation and other mechanical variables in the model. The results show that digitization increases the quantity of green innovation by increasing environmental uncertainty but only significantly improves the quality of green innovation. These results may be because firms face a new digital market environment after choosing digital transformation. While benefiting from the convenience of digital technology, digitalized companies will face new issues such as market monopoly, tax erosion, and data security. These risks and challenges will bring more uncertainty to the business environment and volatility to the marketing revenue of

TABLE 10 Heterogeneous effect analysis.

Panal A: High-tech enterprises				
VARIABLES	(1)	(2)	(3)	(4)
	High-tech firms	High-tech firms	Non-high-tech firms	Non-high-tech firms
	lnGTP	lnGTP	lnGTP	lnGTP
L.lnDIG	0.018**	0.002	0.018**	0.001
	(0.009)	(0.007)	(0.008)	(0.005)
Control variables	YES	YES	YES	YES
Observations	15,700	10,630	15,700	10,630
R2	0.143	0.067	0.113	0.048
Empirical p-value	-0.024***		-0.022***	
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES
Panal B: Heavy Pollution industry				
VARIABLES	(1)	(2)	(3)	(4)
	Heavy pollution industry	Heavy pollution industry	Non-heavy pollution industry	Non-heavy pollution industry
	lnGTP	lnGTP	lnGTP	lnGTP
L.lnDIG	-0.007	0.019***	-0.004	0.017***
	(0.011)	(0.007)	(0.008)	(0.006)
Control variables	YES	YES	YES	YES
Observations	7,720	18,858	7,720	18,858
R2	0.099	0.114	0.073	0.089
Empirical p-value	0.045***		0.037***	
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES
Panal C: State Ownership				
VARIABLES	(1)	(2)	(3)	(4)
	SOE	SOE	Non-SOE	Non-SOE
	lnGIP	lnGIP	lnGIP	lnGIP
L.lnDIG	0.008	0.021**	0.007	0.019***
	(0.009)	(0.008)	(0.007)	(0.007)
Control variables	YES	YES	YES	YES
Observations	10,354	16,304	10,354	16,304
R2	0.126	0.102	0.103	0.075
Empirical p-value	0.013		0.011*	
Year fixed effects	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES

Robust standard errors are reported in the parentheses; ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

enterprises. At the same time, this will also motivate firms to develop green innovation and establish a green competitive advantage, thus increasing the quantity of green innovation by firms.

4.3.5 Quantitative decomposition model of mechanisms

In the above sections, we tested the mechanisms related to the digital economy that can affect the green innovation of enterprises through the resource allocation effect, R&D investment effect, corporate governance effect, and environmental fluctuation effect. In order to further test and quantify the above mechanisms, this paper refers to Gelbach (2016) to quantitatively decompose the mechanisms. The contribution of green innovation promoted by the resource allocation effect is 20.70%; the contribution of green innovation promoted by the R&D investment effect is 36.00%; the contribution of green innovation reduced by the environmental uncertainty effect is 8.62%. Although the contribution of the corporate governance effect to green innovation is 0.4%, it is clear from the previous section that this effect does not significantly impact green innovation. The above effects explain 65% of the total impact. This result also shows that the mechanisms above are plausible and indicate that the resource allocation and R&D investment effects strongly influence the digital economy to enhance corporate green innovation.

4.4 Heterogeneous effect analyses

In this section, we examine the impact of digitalization on the green innovation activities of different types of firms by dividing the study sample into three dimensions: technology density, firm pollution, and firm ownership. The results are reported in Table 10.

4.4.1 High-tech enterprises

Under the regulation of market requirements and competition mechanisms, the high-tech industry will focus on developing green products with less pollution and low energy consumption as the focus of the future development of enterprises. It is because most high-tech enterprises are knowledge and technology-intensive, and knowledge integration is an effective way and important mechanism for enterprises to carry out green innovation (Strambach, 2017). Technology can promote open innovation in enterprises, thus encouraging enterprises to engage in green innovation activities (Mubarak et al., 2021). High technology industries are more willing to carry out green innovation and improve the efficiency of resource use in the process of digitalization transformation, and then further enhance the competitiveness of enterprises. Therefore, this paper believes that for high-tech enterprises, digitalization has a greater incentive effect on green technology innovation.

To examine the impact of digitization on firms with different technology densities, we divide the sample firms into groups according to whether they are high-tech firms or not. This paper refers to Peng and Mao (2017) and classifies enterprises in 19 industries as high-tech enterprises in manufacturing, software and information technology services, and scientific research and technology services. Panel A in Table 10 shows the impact of firms on *GTP* and *GIP*. Columns 1) and 3) report that the coefficient of corporate digitalization on green innovation is significantly positive for high-tech firms, while Columns 2) and 4) show that the coefficient for non-high-tech firms is not significant. It shows that corporate digitalization positively impacts high-tech enterprises' green innovation more than other enterprises. These results may be because high-tech enterprises are likelier to have a relatively complete digital infrastructure and strong innovation capabilities, so they can better use the new technology to enhance green innovation capabilities.

4.4.2 Heavy pollution industry

Driven by the new development concept of the country and guided by the government's industrial policies, in the process of sustainable development, it is an inevitable choice for enterprises to gradually reduce pollutant emissions, improve resource utilization efficiency, and gradually eliminate industries with heavy pollution and high resource consumption. Considering the business attributes and industry traits of heavy pollution industries, it is difficult for heavy pollution firms to reduce their pollutant emissions through digitalization, and gradually being eliminated by alternative industries seems to be the default path for industry development, while light pollution firms are more motivated to carry out green technology innovation in the process of digitalization to avoid being eliminated by the government. Therefore, this paper believes that for light pollution industries, digitalization has a greater incentive effect on green technology innovation.

We then investigate whether the motivation of enterprises in heavy pollution industries to green innovation may be more assertive. We classified 16 industries, including coal, mining, textile, paper making, pharmaceutical, and chemical, as heavy pollution following the Classified Management Directory of Environmental Protection Verification Industries of Listed Companies formulated by the Ministry of Environmental Protection of China in 2008. The results are presented in panel B of Table 10.

All empirical *p*-values of the regression are significant, allowing us to compare the coefficients of the two regression groups. Columns 1) and 3) show that the regression coefficient of enterprises belonging to heavy pollution industries is insignificant. In contrast, the coefficient of enterprises belonging to non-heavy pollution industries is positive and significant at a 1% level. The results show that enterprises in non-heavy pollution industries can better promote green innovation through digital transformation.

For industries such as coal mining and paper making, which generate massive pollution, digitalization cannot fundamentally change the fact that these industries need to produce through massive pollution. Therefore, the incentives for such enterprises' green innovation activities are insignificant.

4.4.3 State ownership

State-owned enterprises play an important role in China's economic structure and provide a research perspective for studying the heterogeneous effects of ownership on the digital economy. Compared with non-state-owned enterprises, China's state-owned enterprises face smaller financing constraints and have more political resources, so state-owned enterprises have a greater ability to make a green investment. In addition, as state-owned enterprises assume more political views, they will actively invest in green innovation projects in the context of the Chinese government's increasing emphasis on green and innovative development. Therefore, the green innovation activities of state-owned enterprises are less constrained by financing constraints and more pressured by political tasks. On the contrary, the development of the digital economy has less impact on their green innovation strategies. On the contrary, non-state-owned enterprises face greater financing

TABLE 11 Digitalization in four dimensions.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	lnGTP	lnGTP	lnGTP	lnGTP	lnGIP	lnGIP	lnGIP	lnGIP
DTA	0.010* (0.006)				0.011** (0.005)			
IBD		0.003 (0.006)				0.004 (0.005)		
IMA			0.014** (0.005)				0.010** (0.004)	
MISA				0.015*** (0.005)				0.012*** (0.004)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES
Observations	26,658	26,658	26,658	26,658	26,658	26,658	26,658	26,658
R2	0.108	0.108	0.109	0.109	0.083	0.083	0.083	0.083
Number of firms	3,240	3,240	3,240	3,240	3,240	3,240	3,240	3,240
Year fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Firm fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Industry fixed effects	YES	YES	YES	YES	YES	YES	YES	YES

Robust standard errors are reported in the parentheses;***,** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

constraints and various resources, and the digital economy can better play the governance effect and resource allocation effect to improve their willingness and ability to invest in green innovation. Therefore, this paper argues that for SOEs, the incentive effect of digitalization on green technology innovation generated by them is greater.

Therefore, we empirically investigate whether the impact of firm digitization on green innovation varies with firm ownership. The results in Table 10 show that the coefficient is significant at the 1% level for non-state-owned firms, while it is not significant for state-owned firms. The results suggest that digital transformation is more critical in achieving better green innovation outcomes for non-state-owned firms than private firms.

These results may be due to the different enterprise structures. Non-SOEs have fewer resources and higher financing constraints, so digital transformation can help non-SOEs achieve green innovation and form the market's competitiveness of non-SOEs.

4.5 Further analyses

To further investigate which dimensions of digital development have influenced the level of corporate green innovation. We used text analysis referring to Wang et al. (2020), by converting the annual reports of listed companies from 2008 to 2020 into text format. We then filtered the high-frequency words related to digital transformation by python's crawler function. We divided them into digital technology applications (DTA), internet business models of digitalization (IBD), intelligent manufacturing applications (IMA), and modern information system applications ($MISA$). Among them, words such as data management and cloud computing represent digital technology applications; words such as internet platform and e-commerce represent internet business models of digitalization; words such as industrial intelligence and automatic control represent intelligent manufacturing applications; and words such as information sharing and information communication represent modern information system applications. We then counted the word frequencies of each dimension, and standardized the data of word frequency. Finally, we used the entropy value method to determine the weight of each index, and considered the results as indices of different dimensions of digitalization.

The results in Table 11 show that digital technology applications, intelligent manufacturing applications, and modern information system applications are the three main approaches to promoting green innovation. Columns 1) and 5) show that digital technology application has a 5% and 10% significance level, respectively. Columns 3) and 7) show that intelligent manufacturing application has a 5% significance, and columns 4) and 8) show that modern information system application is more likely to promote green innovation in the company at a 1% significant level. In contrast, internet business models of digitalization do not significantly contribute to corporate green innovation. The results show that modern information system application promotes the quantity and quality of green innovation more than other approaches. Therefore, enterprises need to prioritize the development of modern information systems and strengthen information sharing ability. Secondly, consider optimizing the application of digital technology in manufacturing processes and data platforms, which can help improve the level of green innovation in enterprises. Finally, the excessive investment of enterprises in e-commerce development may not benefit corporate green innovation.

5 Conclusions, implications, and limitations

In the background of global green transformation, green technology innovation is an inevitable requirement for achieving high-quality development. The rapid two-way integration of the digital and real economy has led to the continuous optimization of industrial structure. Based on the annual reports of Chinese listed companies from 2008 to 2020, this paper obtains each company's annual digital transformation information using the text recognition method and constructs a database of corporate digitalization. By matching the

digitalization indices with the green innovation and financial data of enterprises, this paper empirically studies the association between corporate digital transformation and green innovation. Based on the empirical results, this paper draws the following conclusions:

- Corporate digitalization can improve the substantive green innovation of enterprises.
- Digital technology applications, intelligent manufacturing applications, and modern information system applications are the three main models of corporate digitalization to promote green innovation.
- The internet business model application cannot promote corporate green innovation.
- The increase in government subsidy and corporate own R&D investment contribute to the incentive effect mentioned above, while the loss of governance efficiency and fluctuation of the external environment offset this effect.
- Compared to other enterprises, this incentive effect is more prominent in non-state-owned, high-tech, and lower-polluted industry enterprises.

Based on the above research conclusions, to give better play to the incentive role of the digital economy promoting corporate green innovation and realizing corporate green growth, this paper puts forward the following policy recommendations. First, the government should promote the application of digital technology in enterprise production to enable enterprises to achieve sustainable development through digitalization. Our study shows that digitalization can stimulate enterprises to carry out green technology innovation and achieve the integration of enterprise development and sustainable production. Therefore, government departments should encourage enterprises to promote cloud computing, blockchain, digital simulation, big data analysis, and other technologies in production, management, and innovation. In addition, the government can build a sustainable R&D innovation system based on digital technology to enable enterprises to achieve intelligent environmental governance and green production with digitalization.

Second, enterprises should use digital technology to strengthen the construction of internal and external information-sharing platforms to enhance their governance level. This study shows that corporate digitalization can promote enterprise green technology innovation by improving the governance level. Therefore, enterprises should strengthen the application of digital technology in production and manufacturing, energy consumption management and control, supply chain and other processes, rely on digital technology to realize the sharing of internal and external knowledge and information, invest more in green R&D projects, and improve the efficiency of green technology innovation.

Third, in the context of the rapid development of the digital economy, environmental protection departments should use fiscal and tax means to guide green investment in the capital market. This paper finds that external environmental regulation and capital market investment will affect the incentive effect of corporate digitalization promoting green. Enhancing government subsidies is one mechanism behind corporate digitalization that promotes green innovation. Therefore, the government should adopt various policies, such as taxation and financial subsidies, to guide the capital market to invest in corporate green projects to encourage enterprises better to invest in environmental protection and enhance environmental governance capability. In addition, give non-SOEs with higher financing constraints, taxation and financial subsidies are important external financing for them. Therefore, the government can provide more taxation and financial subsidies for the digital projects of non-SOEs to encourage their digitalization.

Forth, the government should adopt different digital development policies for different enterprises. This paper finds that the promotion of corporate digitalization on innovation has a heterogeneous effect. As high-tech enterprises are the main force of digital technology innovation and application, the government should introduce incentive policies to ensure their digital development. For SOEs who have enough financing and resources, the government can encourage their digitalization through administrative guidance rather than financial support. For polluting enterprises, the government can implement constraint policies to guide their digitalization and green development.

However, this paper still has some limitations, which point out the direction for future research. First, corporate digitalization is a more complex and gradually evolving concept. Although this paper obtains enterprise digital transformation by identifying digital keywords in the company's annual reports, the indices we use still cannot directly reflect the application of digital technology in enterprises. Subsequent research can measure corporate digital transformation by direct evidence of their application of key digital technologies. Second, the research object of this paper is China's listed companies, which may not represent the digital economy practice of other countries or non-listed companies. On the one hand, due to China's strong support for digital technology and implementation of a series of digital strategies in recent years, its domestic digital development is fast, so the digital transformation of Chinese enterprises is also fast. On the other hand, listed companies are often the best in their industries, and their digital technology applications have generally reached the frontier of the industry. Future research can provide more empirical evidence by selecting data from other countries or non-listed companies to expand relevant conclusions.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.gtadata.com/.

Author contributions

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

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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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Can green credit policy under the concept of green economy curb corporate financialization to promote sustainable development?

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Under the concept of green economy, discovering how to utilize the Green Credit Guidelines in a way that guides enterprises to focus on their industries and to promote sustainable development has become an important and urgent objective. It is also conducive to the successful implementation of the "double-carbon target". This paper uses Chinese A-share listed enterprises from 2007–2018 as its research object to explore whether green credit policy is conducive to reducing the financialization behavior of heavily polluting enterprises to curb their transformation from real to virtual. It is found that the financialization of heavily polluting enterprises has significantly decreased since the implementation of the Green Credit Guidelines in 2012, and these results remain unchanged after a series of robustness tests. A heterogeneity analysis shows that state-owned enterprises are subject to stronger policy effects than non-state-owned enterprises; furthermore, the studied policy effects are stronger in the eastern regions of China than in its central and western regions, and these effects are stronger in green provinces than in polluting provinces. A mechanism study finds that credit constraints and corporate innovation play a partially mediating role in the effect of green credit policy on corporate financialization. Further studies find that both the level of internal corporate governance and external monitoring contribute to the disincentivizing effect of green credit policy on financialization. Moreover, through an exploration of the possible economic consequences of the examined policy, it is found that the green credit policy reduces corporate financialization in favor of reducing inefficient corporate investment and major shareholders' tunneling so that the level of corporate investor protection is improved. The findings validate the effectiveness of the Green Credit Guidelines and provide empirical evidence and empirical support for reducing corporate financialization to curb enterprises' transformation from real to virtual and thus promoting the development of sustainability.

KEYWORDS

green credit policy, corporate financial investment, green economy, sustainability, inefficient corporate investment, major shareholders' tunneling

1 Introduction

Since its reform and opening up, China's economy has developed rapidly and has become deeply integrated into internationalization and globalization processes; moreover, with the implementation of China's registration system and the improvement of its capital market, corporate financialization has progressed, and the contribution of the financial sector to GDP has increased. This shows that the role of financial development in the country's economic activities has also increased.

However, the frequent occurrence of environmental pollution and the decline in environmental quality have become important reasons for the sluggish economic development of real enterprises that have accompanied the new state of China's economy. The development of sustainable energy technology and green economy are attracting more and more attention (Sansyzbayeva et al., 2020; Streimikiene, 2022). They are also paying more and more attention to practical issues, such as the energy poverty and impact of COVID-19 pandemics (Streimikiene, 2022) An important problem in China is green development and financial asset allocation. Specifically, heavily polluting enterprises are increasingly transferring real enterprise capital materials to the financial sector to develop the virtual economy; this behavior of allocating funds to financial assets with a high degree of virtualization is the phenomenon of corporate financialization (Demir, 2009). The development of real enterprises that feature excessive engagement in financial business leads to a lack of sufficient support for the development of the real economy, which certainly affects the healthy development of the national economy in the long run. Thus, ways to prevent heavily polluting enterprises from engaging in excessive financial business and to reduce enterprises' transformation from real to virtual have become frequently discussed as key issues related to China's economic development.

Numerous scholars have conducted rich research on corporate financialization. The studies on the economic consequences of corporate financialization include those on the differential impacts of financialized markets on management procedures and risk attitudes (Siepel & Nightingale, 2014), the possible positive impact of financialized markets on corporate governance (Matsumoto, 2020), the decline in entity investment due to financialization (Maria Diez-Esteban et al., 2016; Davis, 2017; Jin et al., 2022), the impact of the financialization of the non-financial sector on its economic growth (Tomaskovic-Devey et al., 2015), the decrease in the financialization of the functional income distribution (Kohler et al., 2018), the possibly negative effect of corporate financialization on corporate environmental responsibility (Li et al., 2020), and the possibility for financialization to lead to a decrease in the share of wages (Kohler et al., 2019). Thus, this demonstrates that the excessive engagement of non-financial capital enterprises in financial business development has certain negative effects on individuals, enterprises, and society, although the development of corporate financialization promotes the rapid development of enterprises to a certain extent; moreover, to curb corporate financialization, it is necessary to explore the reasons behind the influence of corporate financialization. The literature on the causes of corporate financialization mainly covers shareholder value creation pressures (Modell & Yang, 2018), technological and ideological changes (Davis & Kim, 2015), trust structures (Harrington, 2017), employee stock ownership plans (Feng et al., 2022a), business diversification (Feng et al., 2022b), multiple blockholders (Jiang et al., 2022), and increases in the cash holdings of non-financial firms, and it provides support for the possibilities that traditional non-financial firms are increasingly engaging in for-profit lending (Davis, 2018). While most of these influences have been studied only in terms of corporate behavior and social relations, few studies have explored how institutional reforms and related policy implementations can influence corporate financialization. A key factor that drives heavily polluting enterprises to make excessive investments in financial assets is the opportunity to increase free cash flows.

For this reason, the Chinese government has actively explored financial instruments that can be used to effectively manage the pollution and excessive financialization of heavily polluting enterprises in the pursuit of high-quality economic development. For example, on 24 February 2012, the China Banking Regulatory Commission (CBRC) implemented the Green Credit Guidelines, which clarify the standards and principles of green credit in the banking industry and provide effective guidance on how financial institutions can effectively utilize green credit, give full play to the resource allocation efficiency of the financial market, and promote the green transformation of traditional industries to encourage enterprises to improve their environmental quality and establish a low-carbon circular development system. Existing studies on green credit policy mainly focus on policy effects, but the relevant research findings have not been unanimously accepted. For example, on the commercial banking side, green credit has been shown to have a negative impact on commercial bank performance in some cases, but this impact continues to diminish over the long-term implementation of the policy; in contrast, studies conducted based on dynamic templates have found a significant positive impact of green credit policy on the aggregate performance of commercial outcomes (Luo et al., 2021; Yin et al., 2021; Li et al., 2022).

On the business side, some studies have found significant effects of green credit policy implementation in terms of its ability to increase the financing costs of high-pollution and high-energy consumption enterprises, reduce the maturity of debt financing, and thus reduce the environmental impact of the development of heavily polluting enterprises. However, other studies have concluded that the implementation of green credit policies has not achieved the expected effect, that green credit policies only have a restrictive effect on short-term loans and little impact on long-term loans and financing costs and that heavily polluting enterprises can easily still obtain credit (Xu & Li, 2020; Tan et al., 2022a; Li et al., 2022). Scholars have not reached a consensus on the implementation effect of green credit policy, and related issues still need to be further explored. The promulgation of the Green Credit Guidelines indicates the government's determination to govern the financing behavior of heavily polluting enterprises through bank credit (Zhang et al., 2022a), which in turn will influence the financialization decisions of enterprises.

However, few existing studies have focused on the impact of green credit policy on the financialization of heavily polluting enterprises and the underlying mechanism of action. As an economic regulatory instrument of environmental regulation, does green credit policy curb the financialization of heavily polluting enterprises? If so, through what channels does green credit exert this influence on the financial investment behavior of enterprises? Does the impact of green credit on corporate financialization vary across different economic scenarios? The answers to these questions will not only help us further explore the important factors influencing corporate financialization at the macro policy level and gain a deeper understanding of the theoretical logic of

the relationship between macroeconomic policy and micro enterprise behavior but will also provide theoretical references for the implementation of green credit policy to serve the real economy.

Based on this, this paper conducts a study on the relevant issues with a sample of Chinese A-share listed companies covering 2007 to 2018. The relevant findings show that the implementation of the Green Credit Guidelines policy significantly reduced the financialization behavior of heavily polluting enterprises, and these findings remain robust after a series of robustness tests. The relevant findings are more pronounced among state-owned enterprises, in the eastern regions of China and among enterprises in green provinces. The mechanism study finds that Green Credit Guidelines affect corporate financialization mainly through credit constraints and corporate innovation. Further study finds that both the level of internal corporate governance and external supervision enhance the disincentivizing effect of the Green Credit Guidelines on financialization and that the reduction in corporate financialization induced by this green credit policy is beneficial in terms of further reducing the inefficient investments of firms and reducing major shareholders' tunneling.

2 Theoretical analysis and hypothesis formulation

The separation of power in modern enterprises into two components has caused a conflict of interest between managers and the owners of enterprises. Managers tend to excessively pursue short-term goals that benefit themselves, while owners seek to maximize long-term interests; this leads to the possibility that managers may use their management power to earn contractual compensation and excess profits at the expense of owners in the process of making relevant decisions to achieve performance goals or meet personal needs. Moreover, in corporate enterprises, major shareholders often tend to use their control power to disproportionately balance corporate decisions to benefit their personal self-interests against the detriment of the legitimate rights and interests of small and medium-sized shareholders. Among them, using free cash flow by executives to invest in financial products with the goal of obtaining transient high returns is an important means to seek personal gains (Li et al., 2020). Heavily polluting enterprises generally have significant fixed assets and can quickly obtain sufficient credit funds *via* tangible asset guarantees, which in turn may provide additional room for executives to make financial investments for personal gain.

Green credit policies require financial institutions to fully examine the business scope of target enterprises when conducting credit operations, especially in terms of the environmental and social risks pertaining to the enterprises, and they are required to decline the authorization of credit for enterprises that are not friendly to the environment and social development or even those that have serious destructive effects with the objective of reducing their capital investment in polluting enterprises (He et al., 2019; Lyu et al., 2022; Peng et al., 2022; Wang et al., 2022). As environmental regulations become stricter and the "double-carbon target" is implemented, the increasing risk of environmental violations increases the chance that heavily polluting enterprises will not be able to repay their debts (Guo et al., 2022; Lian et al., 2022). Banks, as creditors, bear greater investment risks than shareholders, while corporate managers, in pursuit of their own interests or short-term interests, tend to reduce investment in real enterprises and tend to invest idle funds in financial products; however, investments in financial products entail great uncertainty, and once such an investment fails, a major debt crisis in terms of corporate funds may arise and harm the interests of creditors (Hu et al., 2020; Zhang et al., 2021; Zhu, 2022; Ge and Zhu, 2022). Therefore, banks apply credit rationing to heavily polluting enterprises to mitigate credit and environmental risks and safeguard their own credit quality. The introduction of a green credit policy means that heavily polluting enterprises face a stricter financing environment and that the available credit for heavily polluting enterprises is significantly reduced; this, in turn, reduces available cash flow (Liu & He, 2021; Tan et al., 2022b; Zhang & Zhou, 2022). A green credit policy can reduce the credit resources available to firms and decrease their disposable cash flow. This reduction in management's disposable cash flow forces management to engage in less financial speculation, which helps reduce the financialization of heavily polluting enterprises and curb their transformation from real to virtual. In addition, the introduction of a green credit policy indicates that a greater proportion of limited resources will be allocated to green development enterprises (Liu et al., 2019; Zhang et al., 2022c). In turn, heavily polluting enterprises seeking green credit will actively improve their production processes, increase their R&D investments, and reduce pollution emissions by means of technological innovation (Liu et al., 2021; Zhang et al., 2022d; Gao et al., 2022). Moreover, a focus on technological innovation R&D is conducive to the development of the long-term goals of enterprises, as it reduces the crowding out of entity investment in enterprises and promotes the allocation of more funds to technological innovation, thus discouraging the financialization behavior of enterprises. It can be seen that, on the one hand, the introduction of a green credit policy can alleviate the corporate agency problem to a certain extent by reducing the discretionary cash flow of heavily polluting enterprises and thus reducing the self-interest motivation of executives and the tendency of enterprises to earn speculative profits by investing in financial products; on the other hand, a green credit policy guides heavily polluting enterprises to spend more funds on green technological innovation and transformative development and thus reduce their financial investment. Accordingly, this paper proposes the following hypothesis.

Hypothesis: After the implementation of a green credit policy, the financialization behavior of heavily polluting enterprises is significantly reduced, which curbs their transformation from real to virtual.

3 Research design

3.1 Sample selection and data sources

In this paper, Chinese A-share listed companies are selected as the research sample, and the chosen research interval spans from 2007 to 2018. The year 2007 is chosen because the new accounting standards of China were implemented in 2007; since new financial instrument standards were implemented after 2019, in order to ensure consistent measurement of variables in this paper, the sample was selected as of 2018; moreover, we exclude observations of financial companies, observations of ST and PT

TABLE 1 Definition of variables.

Variable type	Variable symbol	Variable name	Definition
Dependent variable	FIN	Corporate financialization	Financial investment assets/Total assets
Independent variable	POST×TREAT	Net effect of the green credit policy	For years after 2012, the value of POST is 1; otherwise, it is 0. When the enterprise is in a heavily polluting industry, the value of TREAT is 1; otherwise, it is 0
Control variable	SIZE	Firm size	Natural logarithm of total assets
	LEV	Leverage	Total liabilities/total assets
	ROA	Return on total assets	Net profit/total assets
	PAY	Executive compensation	Sum of top three executives' compensation/total assets
	BSIZE	Board size	Natural logarithm of the number of board members
	INDEP	Independent director size	Number of independent directors/number of directors on board
	TOP2_10	Equity checks and balances	The sum of the shareholdings of the second-largest shareholder to the tenth-largest shareholder of the company
	DUAL	CEO duality	A dummy variable equal to 1 for firms where the chairman and general manager are the same person and 0 otherwise
	BM	Book-to-market ratio	Total assets/total market value

companies, observations of companies listed for less than 1 year, observations of companies with asset-liability ratios greater than 1, and observations with missing data. All continuous variables are winsorized at the 1% and 99% percentiles, and a final sample of 19,914 valid observations is obtained. This study utilizes financial data from the China Stock Market and Accounting Research Database (CSMAR), the RESSET financial research database, and the Chinese Research Data Services Platform (CNRDS).

3.2 Variable definitions

3.2.1 Corporate financialization

Referring to existing scholars such as Demir (2009), the ratio of financial investment assets to total assets is chosen as a measure of financialization. Specifically, the sum of "trading securities," "derivative instruments," "available for sale securities," "held-to-maturity securities," "long-term equity investments," and "investment properties" is used as a measure of financial investment assets, and the ratio of financial investment assets to total corporate assets is used as a measure of corporate financialization (FIN).

3.2.2 Green credit

Based on existing scholarly studies (Wen et al., 2021; Zhang et al., 2022b), a relevant study design is used. POST×TREAT is the net effect of the green credit policy, and the dummy variable POST is created for the experimental period according to the difference-in-difference model. For the year 2012 or later years, the period after the promulgation of the Green Credit Guidelines, this variable is set to 1, while it is set to 0 for the years before 2012. In addition, the dummy variable TREAT denotes whether each sample enterprise is a heavily polluting enterprise. If the enterprise is a heavily polluting enterprise, TREAT takes the value of 1; otherwise, it takes the value of 0.

3.2.3 Control variables

The control variables include firm size (SIZE), the gearing ratio (LEV), return on total assets (ROA), executive compensation (PAY), board size (BSIZE), independent director size (INDEP), equity checks and balances (TOP2_10), dual position (DUAL), and the book-to-market ratio (BM); moreover, annual and individual effects are controlled in the subsequent regression process. The relevant variables are defined in Table 1.

3.3 Regression model

To test hypothesis 1, the following model is constructed:

$$FIN_{it} = \alpha_0 + \alpha_1 POST_{it} \times TREAT_{it} + \alpha_2 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (1)$$

In the above equation, μ_i represents individual firm fixed effects, μ_t denotes time fixed effects, and ε_{it} is the error term. Moreover, α_1 is the focus of attention in this paper, and it denotes the regression coefficient of POST×TREAT, which mainly measures the net effect of the financialization of heavily polluting enterprises relative to that of non-heavily polluting enterprises. If α_1 is significantly negative, this indicates that the studied green credit policy reduces the financialization of heavily polluting enterprises and curbs their transformation from real to virtual.

4 Test results and analysis

4.1 Descriptive statistics

The descriptive statistics of the sample are shown in Table 2. According to this table, the mean value of FIN is 0.022, indicating that the ratio of financialized investment to the total assets of the sample enterprises reaches 2.22%; moreover, the standard deviation of FIN is

TABLE 2 Descriptive statistics of the variables.

	N	Mean	sd	p25	p50	p75	min	max
FIN	19,914	0.022	0.057	0	0	0.012	0	0.312
POST×TREAT	19,914	0.202	0.402	0	0	0	0	1
SIZE	19,914	22.204	1.268	21.306	22.032	22.931	19.665	26.086
LEV	19,914	0.456	0.204	0.297	0.457	0.612	0.05	0.928
ROA	19,914	0.04	0.066	0.014	0.036	0.067	−1.146	0.669
PAY	19,914	0.001	0.001	0	0	0.001	0	0.004
BSIZE	19,914	2.16	0.201	2.079	2.197	2.197	1.609	2.708
INDEP	19,914	0.371	0.053	0.333	0.333	0.400	0.308	0.571
TOP2_10	19,914	21.174	12.74	10.634	19.698	30.15	2.055	55.956
DUAL	19,914	0.786	0.410	1	1	1	0	1
BM	19,914	0.612	0.243	0.423	0.609	0.8	0.117	1.143

0.057, and the minimum and maximum values are 0.000 and 0.312, respectively, indicating that there is a certain degree of variation in the financialized investment of different enterprises. The distribution of the remaining control variables is basically consistent with the results of prior literature.

4.2 Analysis of regression results

In this paper, the impact of the green credit policy on corporate financialization is tested based on model 1). Column (1) of Table 3 examines the effect of the green credit policy on corporate financialization with no addition of other variables, and the estimated coefficient of the green credit policy variable is −0.022 and significantly negative at the 1% level; column 2) further adds several control variables, and the coefficient of POST×TREAT remains unchanged at −0.022 and significant at the 1% level. This result indicates that the green credit policy significantly reduces the financialization of heavily polluting enterprises compared to that of non-heavily polluting enterprises, which in turn curbs these enterprises' transformation from real to virtual. This validates hypothesis H1 of this paper.

5 Robustness tests

5.1 Parallel trend test

The use of a difference-in-difference model presupposes that the assumption of parallel trends is satisfied between the experimental and control groups. Specifically, for the context of this paper, before the introduction of the Green Credit Guidelines, the financialization of heavily polluting and non-heavily polluting enterprises should show essentially the same trend of change; however, after the introduction of the Green Credit Guidelines, the two should begin to show significant differences. That is, after the implementation of the green credit guidelines, the policy effects of heavily polluting enterprises and non-heavily polluting enterprises show different trends, and the reason for this change is the impact of policy implementation. Figure 1 reports the results of the parallel trend test of this paper. It can be seen that all the regression results before 2012 are non-significant, which shows that the changes in the trends of financialization for heavily polluting enterprises and non-heavily polluting enterprises are consistent and not significantly different before the introduction of the Green Credit Guidelines. From 2012 onward, the financialization of heavily polluting enterprises decreases significantly compared to that of non-heavily polluting enterprises. This difference is because the implementation of green credit policy has different effects on heavily polluted enterprises and non-heavily polluted enterprises, that is, the implementation of policy does have differences between the experimental group and the control group. Therefore, the sample passes the parallel trend test required for a difference-in-difference estimation.

5.2 PSM-DID method

Considering that firm characteristic differences may vary across heavily and non-heavily polluting enterprises and that these differences may have an impact on the corporate financialization affected by the green credit policy, we attempt to mitigate endogeneity problems using the PSM method. The propensity scores are calculated according to observed characteristics influencing the policy operation, for the purpose of controlling selection bias (Lechner, 2002). Specifically, the nearest neighbor matching method is used to pair heavily and non-heavily polluting enterprises, and this is followed by DID regression; the corresponding regression results are shown in Table 4. From this table, it can be found that the coefficient of POST×TREAT remains significantly negative, and the conclusions of this paper remain unchanged.

5.3 Placebo test

On the one hand, we conducted a time counterfactual test. To ensure that the core dependent variable of this study is affected by the introduction of the Green Credit Guidelines rather than other exogenous shocks, we advance the time when the sample is

TABLE 3 Main regression.

	1)	2)
	FIN	FIN
POST×TREAT	−0.022***	−0.022***
	(−5.760)	(−5.741)
SIZE		−0.002
		(−1.023)
LEV		−0.005
		(−0.712)
ROA		0.005
		(0.435)
PAY		1.277
		(0.503)
BSIZE		0.008
		(1.065)
INDEP		−0.018
		(−0.935)
TOP2_10		−0.000***
		(−4.724)
DUAL		0.003
		(1.270)
BM		−0.024***
		(−5.168)
YEAR	YES	YES
FIRM	YES	YES
_cons	−0.010***	0.041
	(−6.347)	(0.957)
N	19,914	19,914
Adj-R^2	0.257	0.262

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

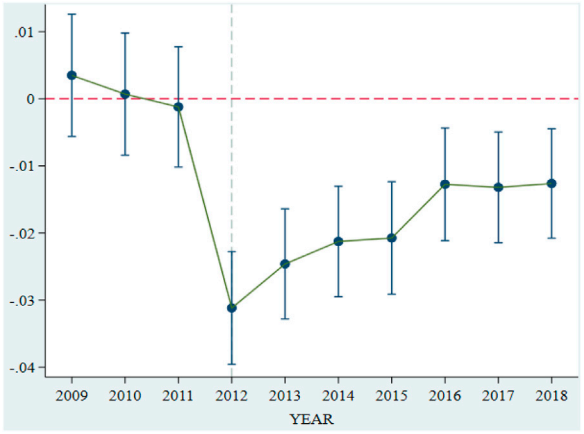

FIGURE 1
Parallel trend test.

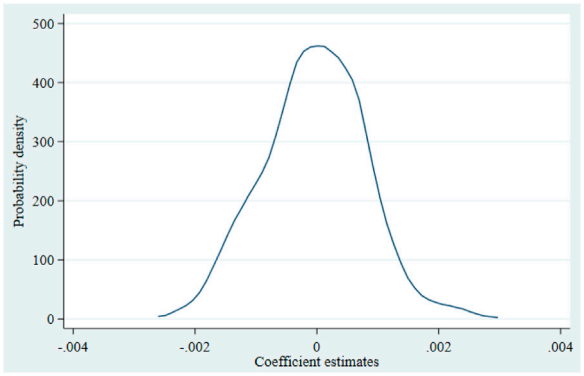

FIGURE 2
Placebo random sampling 500 times of green credit and financialization results.

subjected to shocks by 2 years, i.e., we assume that 2010 is the year in which the virtual shock occurs, and hence, we set POST equal to 1 for the year 2010 and the following years, and we set POST equal to 0 for the years before 2010. If the above findings are due to unobservable inherent differences between heavily and non-heavily polluting enterprises caused by the time frame of the introduction of the Green Credit Guidelines, then the virtual time of the introduction of the Green Credit Guidelines should also be concluded invariantly. The specific regression results are listed in Table 5, and they show that the regression coefficient of POST×TREAT is no longer significant; thus, the hypothesis of this paper is further verified.

On the other hand, we conducted a placebo test in the randomized treatment group and the control group. To further exclude the influence of other unknown factors on firm selection and ensure the reliability of this paper's conclusions, the original study findings are tested for robustness through a random selection of a number of dummy experimental groups from all the samples for a same-baseline regression, the results are shown in Figure 2. The regression coefficients of the fictitious cross-products are all concentrated around zero, indicating that the virtual treatment effect constructed in this paper does not exist and that the green credit policy has no effect on the choice of enterprises. The credit policy has no significant effect in any of the 500 random samples. That is to say, there is a clear correlation between the policy effect discussed in this paper and the implementation of green credit policy. The implementation of green credit policy is the real factor affecting the conclusion of this paper. Therefore, the inhibitory effect of the green credit policy on corporate financialization has little causal relationship with other unknown factors.

5.4 Replacement of the financialization metric

In addition to the aforementioned categories, financial assets should include five balance sheet accounts, namely, "other

TABLE 4 PSM-DID.

	1)	2)
	FIN	FIN
POST×TREAT	−0.020***	−0.018***
	(−2.943)	(−2.581)
SIZE		−0.003
		(−0.785)
LEV		−0.008
		(−0.603)
ROA		0.038
		(1.357)
PAY		−4.706
		(−0.582)
BSIZE		0.028*
		(1.865)
INDEP		−0.032
		(−0.693)
TOP2_10		−0.000**
		(−2.382)
DUAL		0.003
		(0.571)
BM		−0.034***
		(−3.188)
YEAR	YES	YES
FIRM	YES	YES
_cons	−0.010***	0.027
	(−2.587)	(0.323)
N	4,405	4,405
Adj-R^2	0.271	0.279

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

TABLE 5 Time counterfactual test, 2 years ahead.

	1)	2)
	FIN	FIN
POST×TREAT	0.000	0.002
	(0.025)	(0.148)
SIZE		0.010
		(1.259)
LEV		−0.027
		(−0.935)
ROA		0.133***
		(3.272)
PAY		−9.143
		(−1.116)
BSIZE		−0.076***
		(−2.705)
INDEP		−0.017
		(−0.215)
TOP2_10		−0.001***
		(−3.504)
DUAL		0.006
		(0.705)
BM		0.009
		(0.483)
YEAR	YES	YES
FIRM	YES	YES
_cons	0.121***	0.111
	(9.415)	(0.646)
N	19,914	19,914
Adj-R^2	0.033	0.035

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

receivables", "buying back the sale of financial assets", "current portion of non-current assets", "other current assets" and "other non-current assets" (Li et al., 2020). According to the results shown in Table 6, the regression coefficient of POST×TREAT is still negative and significant at the 1% level when the control variables are not included; moreover, the results are negative and significant at the 1% level when the control variables are included, and the relevant conclusions are still valid.

5.5 Excluding the policy introduction year

Since the Green Credit Guidelines were introduced in 2012, 2012 is excluded from the sample study interval to prevent possible measurement error problems. In other words, the portion of the sample corresponding to 2012 is excluded from the aforementioned research design, and the regression test is conducted again. The correlation results are presented in Table 7. The regression coefficient of POST × TREAT remains significantly negative at the 1% level, and the findings remain unchanged.

5.6 Removal of real estate industry samples

Considering that the real estate industry is recognized as a profitable industry, that the financialization of the corresponding commodities has shown an increasing trend in China, and that in a certain sense, real estate can be defined as a commodity with a high financialization level (Davis, 2017), all real estate industry observations in the original sample are removed and the regression test is conducted again; the results are presented in Table 8. The TREAT regression coefficient remains significantly negative at the 1% level, and the conclusion that the Green Credit Guidelines are

TABLE 6 Replacement of financialization measures.

	1)	2)
	FIN	FIN
POST×TREAT	−0.010***	−0.010***
	(−6.965)	(−6.963)
SIZE		−0.002*
		(−1.828)
LEV		−0.002
		(−0.745)
ROA		0.004
		(0.889)
PAY		−0.367
		(−0.344)
BSIZE		0.004*
		(1.647)
INDEP		−0.001
		(−0.079)
TOP2_10		−0.000***
		(−4.104)
DUAL		0.000
		(0.061)
BM		−0.010***
		(−5.240)
YEAR	YES	YES
FIRM	YES	YES
_cons	−0.004***	0.028
	(−6.244)	(1.557)
N	19,914	19,914
Adj-R^2	0.238	0.242

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

TABLE 7 Excluding the year of policy introduction.

	1)	2)
	FIN	FIN
POST×TREAT	−0.019***	−0.019***
	(−5.037)	(−5.005)
SIZE		−0.002
		(−0.969)
LEV		−0.004
		(−0.512)
ROA		0.005
		(0.393)
PAY		1.866
		(0.743)
BSIZE		0.011
		(1.390)
INDEP		−0.026
		(−1.340)
TOP2_10		−0.000***
		(−3.910)
DUAL		0.002
		(0.879)
BM		−0.022***
		(−4.607)
YEAR	YES	YES
FIRM	YES	YES
_cons	−0.009***	0.033
	(-6.086)	(0.800)
N	18,241	18,241
Adj-R^2	0.256	0.261

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

conducive to reducing the financialization of heavily polluting enterprises and thus curbing their transformation from real to virtual remains unchanged.

6 Further research and analysis

6.1 Heterogeneity analysis

The first is the analysis of the heterogeneity of Nature of ownership. Due to the special nature of state-owned enterprises, government policy support tends to favor these firms; moreover, even if state-owned enterprises make financial investments and suffer unaffordable losses, due to the existence of soft budget constraints, the government tends to provide state-owned enterprises with support in the form of subsidies and tax cuts to ensure their stability. Furthermore, compared to non-state-owned enterprises, state-owned enterprises have a lower degree of financing constraints (Wang et al., 2020), which leads state-owned enterprises to make more financial investments. However, green credit has a stronger punitive effect on heavily polluting state-owned enterprises, and heavily polluting state-owned enterprises face stronger constraints on credit financing than non-heavily polluting state-owned enterprises. Thus, green credit policies may lead to restrictions on available liquidity for heavily polluting state-owned enterprises and may reduce their financialized investments. For this reason, the sample of this paper is divided into a sample group of state-owned enterprises and a sample group of non-state-owned enterprises for regression purposes, and the regression results are presented in columns (1) and (2) of Table 9. The regression coefficient of POST×TREAT is −0.029, which is significant at the 1% level in the sample group of state-owned enterprises; however, in the sample

TABLE 8 Removing real estate industry samples.

	1)	2)
	FIN	FIN
POST×TREAT	−0.018***	−0.018***
	(−4.869)	(−4.812)
SIZE		−0.003
		(−1.408)
LEV		−0.003
		(−0.450)
ROA		0.008
		(0.631)
PAY		0.484
		(0.194)
BSIZE		0.009
		(1.106)
INDEP		−0.026
		(−1.447)
TOP2_10		−0.000***
		(−4.452)
DUAL		0.002
		(0.834)
BM		−0.023***
		(−5.385)
YEAR	YES	YES
FIRM	YES	YES
_cons	−0.010***	0.059
	(−5.852)	(1.390)
N	18,862	18,862
Adj-R^2	0.249	0.255

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

group of non-state-owned enterprises, the regression coefficient is −0.010, and it fails the significance test, and the empirical p-value is 0, with a significant difference in coefficients between groups. This indicates that the inhibitory effect of the green credit policy on corporate financialization is more pronounced among heavily polluting state-owned enterprises than among heavily polluting non-state-owned enterprises.

The second is the analysis of regional heterogeneity. Due to the wide geographical dispersion of Chinese enterprises, the eastern region of China tends to have better economic development and a higher level of legal management and enforcement than the central and western regions. Considering the lack of economic development in the central and western regions, the environmental governance and protection of these areas may be lower, and enterprises may face looser environmental regulation. Therefore, the credit constraints generated by the green credit policy may have different impacts on enterprises in different regions. In this paper, the full sample of firms is divided into two groups corresponding to the eastern and central-western regions according to the provinces where the firms are registered for testing, and the results are presented in columns (3) and (4) of Table 9. In the eastern region sample, the regression coefficient of POST×TREAT is −0.023, which is significant at the 1% level, while in the central and western region sample, the regression coefficient of POST×TREAT is −0.020, which is significant at the 1% level; moreover, the empirical p-value of the two groups is 0.001, indicating that the phenomenon of decreased financialization among heavily polluting enterprises was significantly reduced after the implementation of the green credit policy. In particular, this phenomenon is more obvious for heavily polluting enterprises located in the eastern region.

Finally, the heterogeneity analysis between green provinces and polluted provinces Similarly, there are differences in environmental pollution across provinces with different environmental attributes due to the common influence of factors such as the natural environment and the industry layouts of different regions. Therefore, the sample is divided into a green province group and a polluting province group. The governments of green provinces tend to pay more attention to every move of polluting enterprises to maintain their existing environmental achievements, and the management and requirements of heavily polluting enterprises are stricter. Therefore, the green credit policy may have a greater impact on heavily polluting enterprises in green provinces. The results of the subsequent grouped regressions are presented in columns (5) and (6) of Table 9. The regression coefficient of POST×TREAT for the green provinces is −0.030, which is significant at the 1% level, while in the polluting provinces, the regression coefficient of POST×TREAT is −0.017, which is significant at the 1% level; both samples have an empirical p-value of 0 and a significant difference in coefficients between groups, indicating that the suppressive effect of the green credit policy on the financialization of heavily polluting enterprises in both green and polluting provinces can have an effect but that it is more pronounced among heavily polluting enterprises in green provinces.

6.2 Mechanism analysis

On the one hand, the previous section finds that the green credit policy increases the cost of access to credit for heavily polluting enterprises and, on the other hand, forces firms to undertake green technological innovation to reduce their idle capital and thus their financial investment. Therefore, there is an increase in the cost of credit and technological innovation, which may be the mediating variable impacting the effect of green credit policy on heavily polluting enterprises. To this end, the following model is designed for specific testing:

$$MED_{it} = \alpha_0 + \alpha_1 POST_{it} \times TREAT_{it} + \alpha_2 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (2)$$

$$FIN_{it} = \alpha_0 + \alpha_1 POST_{it} \times TREAT_{it} + \alpha_2 MED_{it} + \alpha_3 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (3)$$

where MED is the mediating variable, which is the cost of credit and technological innovation, respectively, and the cost of credit is expressed by the loan constraint LOAN, which is the ratio of the sum

TABLE 9 Heterogeneity: nature of ownership.

	1)	2)	3)	4)	5)	6)
	State	Non-state	East	Midwest	Green	Polluted
POST×TREAT	−0.029***	−0.010	−0.023***	−0.020***	−0.030***	−0.017***
	(−6.488)	(−1.629)	(−4.334)	(−3.575)	(−4.562)	(−3.740)
SIZE	−0.006**	−0.006*	−0.001	−0.003	−0.007*	−0.000
	(−2.076)	(−1.715)	(−0.371)	(−1.049)	(−1.744)	(−0.148)
LEV	−0.011	−0.001	−0.008	−0.006	0.001	−0.010
	(−1.188)	(−0.089)	(−0.794)	(−0.528)	(0.041)	(−1.120)
ROA	0.053*	−0.009	0.028	−0.011	0.013	0.004
	(1.954)	(−0.679)	(1.300)	(−0.766)	(0.494)	(0.291)
PAY	1.337	0.637	2.057	0.611	2.010	1.033
	(0.357)	(0.194)	(0.574)	(0.167)	(0.378)	(0.404)
BSIZE	−0.008	0.023*	0.009	0.008	0.019	0.002
	(-0.901)	(1.829)	(0.656)	(0.951)	(1.002)	(0.295)
INDEP	−0.031	0.012	−0.003	−0.033	−0.020	−0.021
	(−1.168)	(0.469)	(−0.120)	(−1.193)	(−0.524)	(−0.961)
TOP2_10	−0.000	−0.000***	−0.000***	−0.000***	−0.000**	−0.000***
	(−1.541)	(−3.373)	(−2.926)	(−3.466)	(−2.017)	(−4.065)
DUAL	0.001	0.005*	0.003	0.003	0.011*	0.000
	(0.297)	(1.675)	(0.722)	(0.979)	(1.882)	(0.024)
BM	−0.016**	−0.017***	−0.027***	−0.019***	−0.012	−0.026***
	(−2.199)	(−2.902)	(−4.274)	(−2.924)	(−1.427)	(−4.889)
YEAR	YES	YES	YES	YES	YES	YES
FIRM	YES	YES	YES	YES	YES	YES
_cons	0.165***	0.059	0.012	0.068	0.108	0.023
	(2.800)	(0.835)	(0.207)	(1.117)	(1.302)	(0.484)
N	9,623	10,291	9,876	10,038	5,815	14,099
Adj-R^2	0.306	0.229	0.286	0.238	0.292	0.251
Diff (*p*-value)	0.000***		0.001***		0.000***	

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, *t*-test values in brackets.

of long-term and short-term borrowing to the total assets of the enterprise; TE is the technological innovation measured by the number of patents granted to the enterprise for inventions. Referring to Baron and Kenny (Baron & Kenny, 1986) regarding the intermediation effect, an analysis is carried out in conjunction with model 1); specifically, if α_1 in model 1) is significant, we continue by evaluating the significance of the coefficient of α_1 in model 2); furthermore, if α_1 in model 2) is also significant, we continue by evaluating the significance of the coefficient of α_1 in model 3) based on the significance of the coefficient of α_2. Moreover, if the coefficient of α_1 in model 3) is not significant but the coefficient of α_2 is significant, this indicates that there is a full mediation effect; however, if both the α_1 coefficient and the α_2 coefficient in model 3) are significant, this indicates that there is a partial mediation effect. The specific regression results are shown in Table 10. Column (1) in Table 10 shows the regression results of the aforementioned model 1), and the regression coefficient of POST×TREAT is significant. Columns (2) and (4) provide the regression results of model (2), and columns (3) and (5) show the regression results of model (3). The regression coefficient of POST×TREAT in column (2) is −0.073, which is significant at the 1% level, indicating that after the implementation of the green credit policy, the loan constraints faced by heavily polluting enterprises were significantly higher than those faced by non-heavily polluting enterprises; in other words, the total loans available to heavily polluting enterprises were significantly lower. The regression coefficient of LOAN in column (3) is 0.112, which is significant at

TABLE 10 Mediation: Loan constraints and the number of patents granted for inventions.

	1)	2)	3)	4)	5)
	FIN	LOAN	FIN	TE	FIN
POST×TREAT	−0.022***	−0.073***	−0.022***	0.038***	−0.021***
	(−5.741)	(−2.673)	(−10.647)	(2.954)	(−5.674)
LOAN			0.112***		
			(2.799)		
TE					−0.007***
					(−4.535)
SIZE	−0.002	0.779***	−0.002	0.062***	−0.002
	(−1.023)	(40.393)	(−1.391)	(6.822)	(−0.805)
LEV	−0.005	1.559***	−0.007	−0.287***	−0.008
	(−0.712)	(23.689)	(−1.368)	(−9.318)	(−0.967)
ROA	0.005	0.775***	0.008	0.047	0.006
	(0.435)	(6.482)	(0.827)	(0.842)	(0.462)
PAY	1.277	−103.520***	1.454	24.812**	1.452
	(0.503)	(−4.999)	(0.927)	(2.559)	(0.573)
BSIZE	0.008	0.149**	0.008*	−0.037	0.008
	(1.065)	(2.286)	(1.700)	(−1.212)	(1.033)
INDEP	−0.018	0.301	−0.017	−0.335***	−0.020
	(−0.935)	(1.527)	(−1.163)	(−3.626)	(−1.064)
TOP2_10	−0.000***	0.001	−0.000***	−0.001*	−0.000***
	(−4.724)	(0.793)	(−5.781)	(−1.851)	(−4.771)
DUAL	0.003	0.006	0.003*	−0.021**	0.003
	(1.270)	(0.258)	(1.789)	(-1.973)	(1.212)
BM	−0.024***	0.039	−0.024***	−0.002	−0.024***
	(−5.168)	(0.763)	(−6.191)	(−0.067)	(−5.188)
YEAR	YES	YES	YES	YES	YES
FIRM	YES	YES	YES	YES	YES
_cons	0.041	1.089**	0.037	5.131***	0.077*
	(0.957)	(2.550)	(1.153)	(25.659)	(1.835)
N	19,914	19,914	19,914	19,914	19,914
Adj-R^2	0.262	0.295	0.144	0.700	0.264

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

TABLE 11 Interaction effect.

	1)	2)
	FIN	FIN
POST×TREAT	−0.057***	−0.054***
	(−4.347)	(−4.840)
INGOV	0.001	
	(0.108)	
INGOV×POST×TREAT	−0.026**	
	(−2.150)	
EXSUP		−0.000
		(−0.382)
EXSUP×POST×TREAT		−0.004***
		(-2.955)
SIZE	0.021***	−0.002
	(2.910)	(−1.280)
LEV	0.065**	−0.005
	(2.513)	(−1.081)
ROA	−0.049	0.004
	(−1.135)	(0.425)
PAY	−15.899*	1.289
	(−1.886)	(0.822)
BSIZE	−0.007	0.008
	(-0.270)	(1.630)
INDEP	0.015	−0.017
	(0.181)	(-1.147)
TOP2_10	−0.001***	−0.000***
	(−3.415)	(−5.773)
DUAL	0.000	0.003*
	(0.005)	(1.753)
BM	−0.078***	−0.024***
	(−4.265)	(−6.131)
YEAR	YES	YES
FIRM	YES	YES
_cons	0.564***	0.033
	(3.584)	(0.998)
N	19,914	19,914
Adj-R^2	0.297	0.144

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

the 1% level, and the regression coefficient of POST×TREAT is −0.022, which is still significant at the 1% level. Therefore, the conclusion that the credit constraint LOAN plays a partially mediating effect in the process of financialization influenced by green credit policy is valid. Similarly, the regression coefficient of POST × TREAT in column (4) is 0.038, which is significant at the 1% level, indicating that the level of technological innovation among heavily polluting enterprises increased after the implementation of the green credit policy when compared to that of non-heavily polluting enterprises. The regression coefficient of TE in column (5) is −0.007, which is significant at the 1% level, and the regression coefficient of POST × TREAT is −0.021,

which is still significant at the 1% level; therefore, the conclusion that technological innovation plays a partial mediating role in the impact of the green credit policy on financialization also holds.

6.3 Interaction: The effect of the level of internal corporate governance and external supervision

The previous section verifies that the studied green credit policy helps reduce the financial investment of heavily polluting enterprises and thus curbs their transformation from real to virtual. Since the financialization behavior of firms largely stems from management's self-interest motivation, finding effective measures to reduce management's self-interest motivation may enhance the effectiveness of the green credit policy in terms of curbing the financialization of heavily polluting enterprises. In view of this, this paper continues to verify the internal governance level, INGOV, and the external supervision level, EXSUP, and we design the following model:

$$FIN_{it} = \alpha_0 + \alpha_1 POST_{it} \times TEEAT_{it} + \alpha_2 ADJ_{it} + \alpha_3 ADJ_{it} \times POST_{it} \times TREAT_{it} + \alpha_4 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (4)$$

where ADJ_{it} indicates the levels of internal governance INGOV and external supervision EXSUP. The larger this indicator is, the higher the internal governance level of the enterprise. In addition, the natural logarithm of the number of environmental administrative penalty cases is selected to measure the external government environmental supervision of the enterprise, that is, EXSUP = ln (number of environmental administrative penalty cases + 1). The rest of the indicators in the model are the same as before.

The regression test results corresponding to model (4) are presented in Table 11. According to column (1) of the table, it can be seen that the coefficient of INGOV×POST×TREAT is −0.026, which is significant at the 5% level, showing that an effective level of internal corporate governance can strengthen the inhibitory effect of the green credit policy on the financialization of heavily polluting enterprises. Similarly, the regression coefficient of EXSUP×POST×TREAT in column (2) is −0.004, which is significant at the 1% level, indicating that external government environmental supervision can also further enhance the inhibitory effect of the green credit policy on the financialization of heavily polluting enterprises.

6.4 Economic consequences

6.4.1 Inefficient investment

On the one hand, we conducted an analysis of inefficient investment. Since excessive investment in financial assets by enterprises will, to a certain extent, limit the development of normal entity investment and because a good green credit policy is conducive to reducing this adverse behavior, such a policy may promote the efficiency of enterprise investment. To verify this view, the following model is constructed for regression testing:

$$NI_{it} = \alpha_0 + \alpha_1 GROWTH_{it-1} + \alpha_2 LEV_{it-1} + \alpha_3 CASH_{it-1} + \alpha_4 AGE_{it-1} + \alpha_5 SIZE_{it-1} + \alpha_6 RET_{it-1} + \alpha_7 NI_{it-1} + \sum YEAR + \sum IND + \varepsilon \quad (5)$$

$$INV_{it} = \alpha_0 + \alpha_1 POST_{it} \times TREAT_{it} + \alpha_2 FIN_{it} + \alpha_3 FIN_{it} \times POST_{it} \times TREAT_{it} + \alpha_4 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (6)$$

Model (5) mainly refers to the work of Richardson (Richardson, 2006) and other practices to measure inefficient investment. NI_{it} is the actual new investment expenditure of firm i in year t, $GROWTH_{it-1}$ is the growth rate of the firm's main business income, LEV_{it-1} is the gearing ratio, $CASH_{it-1}$ is the cash flow position, AGE_{it-1} is the firm's age, $SIZE_{it-1}$ is the firm's asset size, and RET_{it-1} is the firm's stock return. The absolute value of the residuals estimated by the model is the degree of inefficient investment of the company, which is recorded as INV. The larger the absolute value of the residuals is, the higher the degree of inefficient investment, that is, the lower the efficiency of the investment. A positive residual indicates overinvestment, and a negative residual indicates underinvestment.

In model (6), INV denotes inefficient investment, and a correlation regression between overinvestment and underinvestment is conducted. The specific results are listed in columns (1), (2) and (3) of Table 12. The regression coefficient of FIN×POST×TREAT in Table 12 is −0.036 for the full sample, which is significantly negative at the 5% level, indicating that the green credit policy reduces the inefficient investment caused by the financialization behavior of heavily polluting enterprises. The regression coefficient of FIN×POST×TREAT is −0.067 for the overinvestment group and −0.005 for the underinvestment group; however, the results are significant only at the 10% level for the overinvestment group. These results indicate that the green credit policy reduces the inefficient investment caused by overinvestment mainly by reducing the financialization of heavily polluting enterprises.

6.4.2 Major shareholders' tunneling

It has been verified that the green credit policy can reduce the financialization of heavily polluting enterprises and thus curb their transformation from real to virtual. Under this premise, is the implementation of green credit policy conducive to reducing the tunneling behavior of major shareholders and effectively protecting the legitimate rights and interests of small and medium-sized investors? Based on this, we study the impact of the green credit policy on short selling by major shareholders after the further implementation of the green credit policy for heavily polluting enterprises. The following model is designed for regression analysis:

$$TUNNEL_{it} = \alpha_0 + \alpha_1 POST_{it} \times TREAT_{it} + \alpha_2 FIN_{it} + \alpha_3 FIN_{it} \times POST_{it} \times TREAT_{it} + \alpha_4 CONTROL_{it} + \mu_i + \mu_t + \varepsilon_{it} \quad (7)$$

$TUNNEL_{it}$ denotes the tunneling behavior of major shareholders, and the ratio of total connected transactions to operating income, that is, TUNNEL1, and the ratio of net other receivables to total assets, that is, TUNNEL2, are chosen to measure this factor; Moreover, the

TABLE 12 Economic consequences.

	1)	2)	3)	4)	5)
	INV	Overinvestment	Underinvestment	TUNNEL1	TUNNEL2
FIN	0.014	0.022	0.008	1.152	0.003***
	(1.477)	(1.191)	(0.759)	(1.083)	(8.646)
POST×TREAT	−0.005**	−0.001	−0.005***	−10.672***	−0.001
	(−2.546)	(−0.367)	(−2.642)	(−3.877)	(−0.766)
FIN×POST×TREAT	−0.036**	−0.067*	−0.005	−6.074***	−0.001*
	(−2.038)	(−1.831)	(−0.247)	(−2.955)	(−1.733)
SIZE	0.005***	0.010***	−0.001	0.319	−0.002***
	(3.896)	(4.173)	(−0.571)	(0.165)	(−2.900)
LEV	0.021***	0.046***	−0.001	−11.009*	0.018***
	(5.080)	(5.499)	(−0.117)	(−1.666)	(8.971)
ROA	0.095***	0.097***	0.076***	55.077***	−0.022***
	(12.556)	(5.538)	(9.498)	(4.491)	(−5.902)
PAY	0.332	−9.133***	1.611	1162.286	−0.784
	(0.252)	(-3.056)	(1.158)	(0.559)	(−1.224)
BSIZE	−0.005	−0.014	0.002	−0.425	0.001
	(−1.227)	(−1.601)	(0.546)	(−0.065)	(0.400)
INDEP	0.003	−0.000	0.021	1.200	0.008
	(0.235)	(−0.011)	(1.518)	(0.061)	(1.380)
TOP2_10	0.001***	0.001***	0.000***	−0.035	0.000
	(9.529)	(6.630)	(3.677)	(−0.408)	(0.902)
DUAL	−0.002	−0.005*	0.001	−0.315	−0.001*
	(−1.112)	(−1.901)	(0.371)	(−0.141)	(−1.689)
BM	−0.020***	−0.021***	−0.017***	11.241**	−0.002
	(−6.217)	(−3.221)	(−4.698)	(2.213)	(−1.338)
YEAR	YES	YES	YES	YES	YES
FIRM	YES	YES	YES	YES	YES
_cons	−0.054**	−0.147***	0.048	−9.034	0.053***
	(−1.989)	(−2.668)	(1.591)	(−0.211)	(4.015)
N	19,914	8,083	11,831	19,914	19,914
Adj-R^2	0.062	0.058	0.098	0.004	0.028

Note: ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$, t-test values in brackets.

specific regression results are listed in columns (4) and (5) of Table 12. The regression results regarding TUNNEL1 in column (4) of Table 12 show that the regression coefficient of FIN×POST×TREAT is −6.074, which is significant at the 1% level. The regression coefficient of TUNNEL2 in column (5) of FIN×POST×TREAT is −0.001, which is significant at the 10% level, indicating that the green credit policy designed to reduce the financialization of heavily polluting enterprises can indeed reduce the tunneling behavior of major shareholders, thus helping protect the interests of small and medium-sized investors and promoting the sustainable and healthy development of enterprises.

7 Conclusion

7.1 Research conclusions

Green financial policies, as management tools to guide enterprises toward green development, continuously influence their investment and business decisions. This paper uses Chinese A-share listed enterprises from 2007–2018 as research subjects to explore whether green credit policies are conducive to reducing heavily polluting enterprises' transformation from real to virtual. It is found that 1)

the implementation of the Green Credit Guidelines significantly reduced the financialization behavior of heavily polluting enterprises and curbed their transformation from real to virtual firms, and the results are unchanged after a series of robustness tests. It is also found that 2) state-owned enterprises are subject to stronger policy effects than non-state-owned enterprises, that the identified policy effects are stronger in the eastern regions of China than in the central and western regions, and that the policy effects are stronger in green provinces than in polluting provinces. Moreover, 3) credit constraints and corporate innovation play a partly mediating role in the effect of green credit policy on corporate financialization. Additionally, 4) both the level of internal corporate governance and external supervision contribute to the disincentivizing effect of green credit policy on corporate financialization. 5) Green credit policy reduces corporate financialization, the inefficient investment of heavily polluting enterprises and the tunneling behavior of the major shareholders of heavily polluting enterprises, thus improving investor protections. These findings verify the effectiveness of the Green Credit Guidelines and enrich the research on the influencing factors of corporate financialization.

7.2 Theoretical contributions

The main possible contributions of this paper are as follows. 1) Based on the social context of corporate green development, we study the impact of green credit policy on corporate financialization from the perspective of credit policy changes pertaining to commercial banks, which enriches the research content regarding the framework of the relationship between macroeconomic policy and micro corporate behavior. 2) The existing studies on green credit mainly focus on defining concepts and the current status of implementation, and the studies on the impact of green credit mainly focus on financing; however, this paper is devoted to an in-depth study of the relationship between green credit and corporate financialization and to the relevant internal mechanism and possible economic consequences, thus enriching the research on the impact of green credit. 3) The national institutional design of the Green Credit Guidelines is used to study their inhibitory effect on the financialization of heavily polluting enterprises, enriching the research on the impact factors of corporate financialization.

7.3 Implications

The above findings have the following policy implications for further improving green credit policies to play a more effective governance role. 1) Green credit policies have certain effects, and the government needs to provide effective institutional support for the further improvement of the green financial market, give full play to the positive effects of green credit policies, and urge heavily polluting enterprises to proactively pursue new development models and give attention to real business development. 2) For banks and other financial institutions, due to differences in the nature of ownership, the regions in which they are located and the overall environmental regulations of different enterprises, these policy effects vary; thus, the relevant financial institutions should be firmly in compliance with the green development policy, they should comprehensively consider the development difficulties faced by different enterprises, and develop differentiated measures to promote the green, high-quality development of enterprises. 3) Heavily polluting enterprises should also actively adapt to the new trend of green development and actively transform their development to better promote the implementation effect of the green credit policy, reduce their corporate financial investment and allocate more funds to technological innovation and reform and other real business development to initiate a virtuous cycle of sustainable development.

Specifically, on the one hand, we need to improve the green financial information disclosure system by referring to the international prevailing standards and information disclosure methods, effectively solve the problem of green financial information asymmetry, improve the construction of financial infrastructure, and improve the operating efficiency of green financial services.

On the other hand, the government, enterprises and banks need to effectively cooperate and communicate, improve the efficiency of financial resource allocation, ensure the stability and long-term nature of green credit policies, actively prevent and resolve local debt risks, and guide the sustainable development of green economy.

In a word, the green credit policy is of great significance to the development of enterprises, the performance of government functions and the maintenance of social green health. All sectors of society should work together to promote the sound implementation of green credit policy and achieve the stable development of green economy.

7.4 Limitations and future work

When discussing the effectiveness of green credit policies, this study only compares the differences between heavily polluted enterprises and non-heavily polluted enterprises, ignoring that there may be different policy differences between heavily polluted enterprises and heavily polluted enterprises, as well as between non-heavily polluted enterprises and non-heavily polluted enterprises. Subsequent studies can be detailed from this perspective to further clarify the differences in the effectiveness of green credit policies, it provides a new theoretical reference for policy formulation and implementation. In addition, selecting appropriate methods to unify the variable measurement after 2018 and expanding the research sample to the latest year is also the thinking direction for future research.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://cn.gtadata.com/, http://www.resset.cn/, https://www.cnrds.com/.

Author contributions

Writing-original draft, Methodology, Resources, Writing-review and editing GH; Conceptualization, Data curation WS; Formal analysis, Investigation HL; Supervision, Validation, Visualization SZ; Project administration, Software, Funding acquisition JX.

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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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Research on the coopetition relationship and the development of city-industry integration of urban agglomeration under the effect of HSR

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High-speed rail has influenced the evolution of coopetition relationships among regional cities and promoted city-industry integration development within urban agglomerations. Still, the specific impact it brings needs further study. This paper aims to assess how opening high-speed railways affect the economic development and pattern of urban agglomerations along the route under the perspective of city-industry integration, and the mechanism of action of urban agglomerations' coopetition relationships. The study is based on panel data from prefecture-level cities in Jiangxi Province, China, from 2014 to 2018. Through constructing an evaluation model of the degree of city-industry integration and an improved city economic linkage gravity model, we study the changes in the amount of economic linkage and affiliation of cities in Jiangxi Province after the opening of high-speed rail, which can analyze the changes in the structure and interconnectedness of each urban agglomeration. At the same time, an econometric model of the coopetition relationship of urban agglomerations is proposed to study the impact of high-speed rail on the economic cooperation of cities along the route in combination with the city-industry integration. The results show that 1) there are pronounced differences in the level of city-industry integration development of cities along the high-speed railway in Jiangxi Province, and the phenomenon is significantly improved by the improvement of inter-city economic links after the opening of the high-speed railway; 2) When cities enhance their fixed investment (*FI*) and labor force growth (*LG*), it has a significant promotion effect on their development, but will have a suppressing effect on other cities' city-industry integration, while when enhancing industrial concentration and human capital mobility, it can make the city-industry integration development of each city achieve a win-win situation; 3) The opening of high-speed rail enhances the economic ties of cities along the route and the radiation capacity of the original central cities, which is conducive to the formation of new central cities while improving the weak economic ties between urban agglomerations due to their geographical locations. This study proposes some conclusions and suggestions to provide research support for theories related to city-industry integration and policies related to urban agglomeration competition and cooperation under the high-speed rail effect.

KEYWORDS

city-industry integration, high-speed rail effect, coopetition relationship, gravitational model, entropy method

1 Introduction

To achieve a new strategy of city-industry integration, the National Development and Reform Commission (NDRC) announced "Key Tasks of New Urbanization and Urban-Rural Integration Development in 2021." That focuses on enhancing the ability of the central cities of urban agglomerations to radiate and power surrounding areas. With the rapid development of railway traffic mileage, it not only promotes the expansion of construction land along the line but also greatly drives the economic development of urban agglomerations along the route (Zhao et al., 2017). Especially, the evolution of transportation mode represented by high-speed rail is overturning the traditional industry gradient shift, changing the relationship between different cities, and initiating the reconfiguration of urban location space and the change of urban functions. Researching the coopetition relationship of urban agglomerations and city-industry integration development under the high-speed rail effect are significant meanings for each region to seize the opportunities, coordinate urban relationships, enhance cooperation among cities, promote industry division of labor, establish city agglomerations, and realize sustainable development and city-industry integration.

Coopetition is a state of simultaneous competition and cooperation between subjects. It was first formally introduced into strategic management research by Brandenburger and Nalebuff, emphasizing its purpose of seeking common advantages and breaking through the traditional boundaries of the process. The phenomenon of combining competition and cooperation into one opened up a new perspective on the growth of economic mode (Brandenburger and Nalebuff, 1996). Some scholars have studied the coopetition relationship of urban agglomerations by analyzing the characteristics of regional spatial structure. Xie et al. constructed a spatial network based on tourism economic linkages, and used a modified gravity model to study the spatial structure connectivity characteristics of EU countries' tourism economy (Xie et al., 2021). To find the spatial cluster feature of tourist attractions in the Yangtze River delta region, Wang et al. employed the analysis of spatial and social networks, which provides a basis for developing its' cooperation strategies (Wang et al., 2021). Modeling city development level evaluation is a significant way to measure coopetition relationships of different cities. Based on the theory of inter-governmental relationships and resource location, Zhou et al. established the inter-governmental coopetition measures indicators to evaluate the coordinated development level of the Pearl River Delta urban agglomeration (Zhou et al., 2022). Haque took the development of the coopetition relationship of small cities in urban agglomerations as the research goal, built a municipal service performance model from the micro level, and evaluated the urban competitiveness of a colonial city in eastern India (Haque et al., 2021). Hu et al. constructed a promotion game model for local governments and analyzed the influence of coopetition among core cities in the Yangtze River Delta on urban development. In addition, some researchers have

TABLE 1 Evaluation indicators of city-industry integration and their entropy and weight values.

Target layer	System layer	Criterion layer	Indicator	Entropy	Weights (%)
City-industry integration	Industrial development	Industrial scale	Total industrial output	0.7977	8.26
		Industrial quality	Share of non-farm output	0.9283	2.93
			Energy consumption per unit GDP	0.9192	3.30
			Input Intensity Of R&D	0.793	8.45
			Industrial added value	0.8214	7.29
	Urban development	Equipment package	Urban road area *per capita*	0.8954	4.27
			Fixed asset investments	0.8382	6.60
		Environmental Construction	Green coverage in built-up areas	0.8987	4.14
			Public green space *per capita*	0.9179	3.35
			Sewage treatment rate	0.8895	4.51
		Public server	Ten thousand people with doctors	0.8573	5.83
			Number of buses per 10,000 people	0.8855	4.67
			Daily domestic water consumption *per capita*	0.9304	2.84
			10,000 people own hospital beds	0.8884	4.56
		GDP indicator	Capita GDP	0.805	7.96
	Human Development	Income level	Annual *per capita* consumption	0.908	3.75
			Retail sales of social consumer goods *per capita*	0.8481	6.20
		Employment quality	The proportion of the employed population in secondary and tertiary industries	0.904	3.92
		Population quality	The proportion of the urban population	0.8249	7.15

TABLE 2 Evaluation degree of city-industry integration in Jiangxi Province.

Region	Urban development		Industrial development		Human development		City-industry integration	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Nanchang	0.406	1	0.294	1	0.178	1	0.878	1
Yingtan	0.393	3	0.285	2	0.170	2	0.849	2
Jiujiang	0.405	2	0.206	7	0.167	3	0.778	3
Ganzhou	0.326	6	0.269	3	0.102	6	0.697	4
Yichun	0.383	4	0.208	6	0.089	7	0.680	5
Shangrao	0.350	5	0.225	4	0.057	9	0.632	6
Ji'an	0.315	8	0.197	8	0.068	8	0.581	7
Pingxiang	0.325	7	0.211	5	0.037	10	0.573	8
Xinyu	0.252	11	0.160	9	0.125	4	0.537	9
Fuzhou	0.258	10	0.115	11	0.121	5	0.493	10
Jingdezhen	0.267	9	0.152	10	0.026	11	0.445	11

also explored coopetition relationships between different cities from the perspective of the development level and competitiveness of specific industries (Hu et al., 2008). Cao et al. developed a model of tourism competitiveness in terms of the core competitiveness of mountain tourism, the competitiveness of economic environment, and the competitiveness of infrastructure in Enshi Autonomous Prefecture (EAP), China, and emphasized the coopetition relationship among county authorities in their conclusion (Cao et al., 2022). Huang et al. performed the industry production efficiency of the Chengdu-Chongqing economic circle under different strategies by constructing a regional competition and cooperation framework based on the Meta-Frontier D.E.A. model (Huang et al., 2020).

To promote the ordinate development of the regional economy, urban agglomeration along high-speed rail lines must achieve good and orderly coopetition strategies. Enhancing the intrinsic economic linkages can not only prevents the emergency of a wrong competition pattern of "active competition and negative cooperation" between cities, but also stimulates their close cooperation (Zhou et al., 2018). Many scholars have studied the impact of high-speed rail construction on cities from different perspectives. Some of them have used a variety of approaches to study the influence of HSR construction from the viewpoint of population and employment growth, environmental impacts, spatial and temporal structural characteristics, and urban consumption. Kasu et al. used an integrated spatial regression model based on spatial lags and spatial error correlation to study the relevance between intercity passenger rail and population growth and employment growth in the continental United States (Kasu and Chi, 2018). Hiramatsu studied cities in the high-speed rail route in Kyoto, Japan, and developed an interregional computational general equilibrium model based on the behavioral patterns of consumers and producers, which explained the impact of high-speed rail construction on the growth of population and employment in different cities (Hiramatsu, 2018). Li et al. employed fractal theory to construct an urban spatial structure correlation model to study the impact of high-speed rail construction on urban agglomerations' spatial cohesion and spatial correlation (Li et al., 2020). From the perspective of urban consumption, Cai et al. analyzed the spillover of the high-speed rail effect network on the consumption of surrounding cities in China's prefecture-level and above cities based on a spatial econometric model (Cai et al., 2022). Moreover, studies from the perspective of a regional economic structure are more popular. Wang used the methods of centrality and cohesive subgroup analysis to explore the high-speed rail network construction effect on the regional economic structure of the Greater Bay Area (Wang and Zhang, 2021). Zhang et al. constructed a DID estimation model from the perspective of urban agglomeration, and studied the opening of high-speed rail effect on the economic development pattern and its mechanism (Zhang et al., 2022); Wang analyzed the changes in the accessibility of the Beijing-Tianjin-Hebei region and the spatial distribution pattern of economic activities by the construction of high-speed rail at different scales (Wang and Zhang, 2021); Ruan et al. employed technical models and methods such as gravitational model, locational advantage potential model, and Theil coefficient to comprehensively measure the impact of HSR on the regional economic spatial pattern of the Pearl River Delta urban agglomerations, which including three dimensions: regional

TABLE 3 Test results.

Statistics	Double fixed effect	
	Time test	Unit test
F-value	5.37***	7.45***
Chi-square value	52.21***	61.83***

Note: *** represents significance levels of 1%.

TABLE 4 Model calculation results.

	Time fixed	Single fixed	Double fixed
Constant terms	3.50*** (13.08)	5.67** (2.04)	6.13*** (7.92)
FI	0.18** (2.37)	0.33*** (8.19)	0.43** (2.41)
LG	0.18* (1.79)	0.21*** (2.81)	0.18** (2.11)
IC	1.55*** (10.19)	1.35* (1.61)	1.55* (2.04)
HCM	0.76** (2.31)	0.64** (2.33)	0.85*** (11.27)
RD	7.63** (2.47)	6.48*** (8.13)	8.39** (2.36)
UR	1.37 (1.50)	1.66* (−1.81)	1.68 (.93)
SL_FI	−0.85** (2.41)	−0.81** (1.98)	−1.27 (−.84)
SL_LG	−0.17 (.54)	−0.23* (1.84)	−0.16* (1.77)
SL_IC	0.77*** (4.88)	0.63 (**0**.82)	0.98** (−2.13)
SL_HCM	0.066 (**0**.77)	0.081 (**0**.41)	0.15 (−0.74)
Statistics	F = 30.181***, R2 = 0.839	F = 22.688***, R2 = 0.851	F = 28.725***, R2 = 0.897

Note: The value of t is in parentheses. *, ** and *** represent significance levels of 10%, 5%, and 1%, respectively.

economic linkage, regional advantage potential, and regional economic spatial stability (Ruan et al., 2020).

The existing studies on the development of high-speed rail network construction on the level of urban development have mainly focused on the increased range and the increased size. However, they are lacking in some aspects. First, because they mainly focus on the scope and magnitude of the rise, these studies ignore the impact of HSR construction on the structure of urban agglomerations and the relative lack of research on the change in the development status of specific cities in the region. An urban agglomeration generally has one or even more central cities. And the formation of these major cities may be affected by the construction of a high-speed rail network, which changes the urban agglomeration structure and the economic connection with the surrounding areas. Second, although previous studies are conducted for competition among cities, they seldom view the effect of specific variables on neighboring cities based on the urban agglomeration perspective. Under the HSR effect, the way the variables concerning the city-competition relationship affect the development of neighboring cities needs to be analyzed, which provides a basis for formulating industrial development strategies and talent introduction policies in urban agglomerations.

The city affiliation degree indicates the degree of subordination of a city to other cities in terms of economic development. And it reflects the financial structure and coopetition within the region. It is a scientific issue worthy of study. Therefore, it is important to study the coopetition relationship and city-industry integration of urban agglomerations under the high-speed rail effect for regional development. At the same time, based on the present urban agglomeration structure, it is necessary to assess how each variable of the urban coopetition relationship is influenced, and make suggestions for optimization based on the assessment results. This article uses the research object of the underdeveloped urban agglomeration in central China. First, based on the panel data of the urban agglomeration along the high-speed rail line in Jiangxi Province, an econometric model of the coopetition relationship is established to summarize the ways in which different variables affect the neighboring cities. This method explores the coopetition of the urban agglomeration along the high-speed railway line, and evaluates the impact of the relationship on the city-industrial integration. Second, the evaluation index system of city-industry integration is built to evaluate the degree of city-industry integration in Jiangxi province. And the index's weight are currented by the entropy model. Base on that degree, the improved economic gravity model is used to compare the financial connection strength of urban agglomerations along the line before and after the opening of the high-speed railway, and obtained the way of change of the structure of urban agglomerations in Jiangxi Province as well as the economic affiliation. The results of the study provide a theoretical basis for improving the city-industry integration and coordination of coopetition relationships in urban agglomerations in Jiangxi Province.

2 Materials and methods

The spatial econometric theory suggests that certain economic and geographic phenomena or attributes of a region are spatially correlated with neighboring areas, i.e. (Anselin, 2013). It means the cooperative characteristics of inter-city rivalry will dominate the choice of inter-city rivalry strategies, dynamic evolutionary trends, and evolutionary equilibria. The coopetition between different cities is inevitable in the developing process of urban areas along the high-speed rail line, which would primarily affect the city-industry integration. Therefore, researching the cooperation and competition relationship among cities along high-speed rail lines is crucial for the city-industry integration of individual cities and other cities.

2.1 Econometric model of the coopetition relationship

This article explains the characteristics of coopetition in terms of both competition and cooperation, and evaluates the impact on the

TABLE 5 Attractiveness index.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen
Nanchang	——	0.4916	0.4698	0.4425	0.4346	0.4185	0.3982	0.3949	0.3795	0.3596	0.3364
Yingtan	0.5084	——	0.4782	0.4508	0.4429	0.4267	0.4063	0.4029	0.3874	0.3674	0.3439
Jiujiang	0.5302	0.5218	——	0.4725	0.4645	0.4482	0.4275	0.4241	0.4084	0.3879	0.3638
Ganzhou	0.5575	0.5492	0.5275	——	0.492	0.4755	0.4546	0.4512	0.4352	0.4143	0.3897
Yichun	0.5654	0.5571	0.5355	0.508	——	0.4836	0.4626	0.4591	0.4431	0.4221	0.3973
Shangrao	0.5815	0.5733	0.5518	0.5245	0.5164	——	0.479	0.4755	0.4594	0.4382	0.4132
Ji'an	0.6018	0.5937	0.5725	0.5454	0.5374	0.521	——	0.4965	0.4803	0.459	0.4337
Pingxiang	0.6051	0.5971	0.5759	0.5488	0.5409	0.5245	0.5035	——	0.4833	0.4625	0.4371
Xinyu	0.6205	0.6126	0.5916	0.5648	0.5569	0.5406	0.5197	0.5167	——	0.4791	0.4536
Fuzhou	0.6404	0.6326	0.6121	0.5857	0.5779	0.5618	0.541	0.5375	0.5209	——	0.4744
Jingdezhen	0.6636	0.6561	0.6362	0.6103	0.6027	0.5868	0.5663	0.5629	0.5464	0.5256	——

degree of city-industry integration. Considering the comprehensiveness and scientific nature of the model, and combined with the availability of relevant data, the amount of investment and labor force growth are selected as variables representing the regional competition relationship. The level of industry concentration and human capital flow represents the regional cooperation relationship. And the lagged terms of each explanatory variable are introduced to reflect the influence of the competition relationship on the integration of the remaining cities in the region into the city-industry integration. The econometric model of urban competition cooperation relationship is as follows:

$$\ln(100*DCI_{it}) = \alpha_i + \beta_1*FI_{it} + \beta_2*LG_{it} + \beta_3*\ln(IC_{it}) + \beta_4*HCM_{it} + \gamma*Q_{it} + \delta*SL_{it} + \varepsilon_{it} \quad (1)$$

In Formula 1, DCI_{it} is the degree of city-industry integration of city i in the year t. FI_{it} refers to the investment amount in city i in the year t; LG_{it} is the labor force growth in city i in the year t; IC_{it} is the level of industry concentration in city i in the year t; HCM_{it} is the flow level of human capital mobility level in city i in the year t; Q_{it} is control variable including RD_{it} and UR_{it}; RD_{it} is the proportion of scientific research funds in GDP, and UR_{it} is the level of urbanization; SL_{it} is the Spatial lag term of FI_{it}, LG_{it}, IC_{it}, and HCM_{it}; α_i is constant term; ε_{it} is the random error term. β_1, β_2, β_3, and β_4 are the regression coefficients of the four explanatory variables. The economic model of the coopetition relationship are developed to explain the effect of cooperation and competition among cities, which influence the city-industry integration of itself and surrounding cities. The variables including fixed investment (*FI*), labor force growth (*LG*), industrial concentration degree (*IC*), and human capital mobility (*HCM*). Effect ways of those variables are illustrated by comparing the results of their fixed effect model with the spatial terms of them. On the premise that the fixed-effects model of the variable is positive, if its spatial lag term is negative, it indicates that the improvement of the variable will promote the city-industry integration while inhibiting the development of the surrounding cities; if both are positive, the joint development of the city-industry integration will be realized.

2.2 Entropy model

The city-industry integration refers to the integration of industry development and urban function in a specific region, the essence of which is people as the core, the city as the foundation, and industry as the driving force. And the coupling relationship between these three elements is the embodiment of the degree of city-industry integration.

The evaluation model of city-industry integration, a model including various indicators, is employed to appraise the degree of city-industry integration under the high-speed rail effect. To improve the index system, we constructed the evaluation indicator for city-industry integration in the reference literature (Zhou et al., 2016; Zhang and Shen, 2017; Zou and Cong, 2019), as shown in Table 1. And the weights of indicators are calculated by the entropy model, which achieves the objective empowerment of indicators.

The entropy weighting method is an objective weighting approach that determines the weights through the values of evaluation indicators. The principle is that the greater the degree of variation of an evaluation object in a specific indicator, the greater the weight. This paper selects the entropy weight method to measure the development level of city-industry integration. In this method, the impact of high-speed rail on city-industry integration is quantified from the perspective of Jiangxi Province as a whole and from the perspective of each city. Suppose the number of evaluation indicators is m and the number of system layers is n. The calculation steps of the evaluation of the level of development of city-industry integration based on this method are as follows:

$$r_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}} \quad (2)$$

$$r_{ij} = \frac{maxx_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}} \quad (3)$$

$$H_i = -\frac{1}{lnm}\sum_{j=1}^{m} f_{ij} * ln f_{ij} \quad (4)$$

$$w_i^{'} = \frac{1 - H_i}{n - \sum_{i=1}^{n} H_i} \quad (5)$$

$$U_{it} = \sum_{j=1}^{m} w_i * r_{ij} \quad (6)$$

TABLE 6 Economic distance between cities without high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen
Nanchang	——	88.1	79	209.8	123.7	151.8	123.6	156.1	92.8	63.4	187
Yingtan	82.2	——	95.2	219.4	135.9	61.1	132.9	156.5	109.1	88.2	107.4
Jiujiang	75.2	97.1	——	252.1	165.1	215.3	173.2	228.6	143.7	195.5	81.9
Ganzhou	188.2	210.2	237	——	374.8	281.3	89.9	425.3	329.3	360.2	447.7
Yichun	110.3	130.1	155.3	374.8	——	186.1	181.9	45.5	40.2	162.8	325.5
Shangrao	142.5	61.5	212.7	295.9	195.4	——	193.6	217.2	160.4	161.9	170.3
Ji'an	116.6	133.8	171.5	94.7	191.9	193.9	——	306.3	185.2	152.2	323
Pingxiang	149.6	160.2	230.4	454.2	49	221.2	311.2	——	66	212.5	335.5
Xinyu	92.3	115.5	150.2	362.6	44.9	169.4	196.2	68.6	——	130.2	213.6
Fuzhou	56.1	84.8	187.3	358.2	162.2	155.6	146.2	201.4	121.1	——	149.7
Jingdezhen	184.6	114.2	85.1	490.8	346.2	175.9	336.4	344.1	211.8	162.7	——

Formula 2 is the algorithm to conduct the positive indicator, and Formula 3 is the algorithm to perform the negative indicator. x_{ij} is the value *i*th of the system *j*th index, and normalized data is r_{ij}. H_i is the entropy of indicator i, and $f_{ij} = r_{ij} \Big/ \sum_{i=1}^{m} r_{ij}$ in Formula 4 is the normalized value of r_{ij} processed in columns. In Formula 5, $w_i^{'}$ is the index weight. In Formula 6, U_{it} is the indicator of the system, which is the composite score of city-industry integration.

2.3 Economic linkage gravitational model

Econometric linkage is the indicator to measure the degree of economic connection among cities in areas, which not only reveal the power of central cities' expanding and outward radiation capacity, but also reflects the acceptance of central cities' radiation by surrounding cities. Based on the results of city-industry integration degree in each city, we employ the economic linkage gravitation model to manifest the improvement of economic linkages, affiliation and urban agglomeration structure of each city under the high-speed rail. The closeness of economic ties among cities is often measured in economic studies utilizing gravity models, which are generally expressed as follows:

$$\boldsymbol{R_{ij} = K\frac{M_i M_j}{D_{ij}^r}} \tag{7}$$

where R_{ij} indicate the urban economic connection between city *i* and city j; *K* is the gravitational coefficient; M_i and M_j are the mass of city *i* and j; D_{ij}^r is the distance between city *i* and j, which does not necessarily represent the distance in space; *r* is the distance friction coefficient.

In Formula 7, M_i and M_j can be replaced by the degree of city-industry integration parameters proposed in this paper respectively, and it is transformed into Formula 8 as follow:

$$\boldsymbol{R_{ij} = K\frac{Q_i Q_j}{D_{ij}^r}} \tag{8}$$

where Q_i and Q_j are the degree of city-industry integration, respectively. Other parameters are the same as in Formula 7.

In the existing literature, the gravitational coefficient *K* is usually taken to be 1, which means that the attraction of two cities is considered to be equal, which is clearly not the case. In this paper, the gravitational coefficient is corrected by the following Formula 9:

$$\boldsymbol{K_{ij} = \frac{Q_j}{Q_i + Q_j}} \tag{9}$$

where K_{ij} is the attraction index of city *i* by city *j*, and Q_i, Q_j refer to the degree of city-industry integration of cities one and two respectively.

Referring to Wang's research about urban distance, we combined the travel time and traffic cost, and take exhausted costs into them to build the urban distance D_{ij} model (Wang, 2013). Then, the time value, tired recovery, etc. Are transformed into cash costs, which are combined with the traffic cost to the economic distance as urban distance. The model is shown as follow:

$$\boldsymbol{D_{ij} = F_{dist} + F_{time} + F_p} \tag{10}$$

where D_{ij} is the cost of city *i* to city *j* under the shortest travel time; F_{dist} is the distance cost; F_{time} is the time cost; F_p is the cost of recovery. The relevant parameters are expressed as follows:

$$\boldsymbol{F_{dist} = F_{trans} * d_{ij}} \tag{11}$$

$$\boldsymbol{F_{time} = F_{rjgz} * t_{ij}} \tag{12}$$

$$\boldsymbol{F_p = F_{rjgz} * t_{ph}} \tag{13}$$

$$\boldsymbol{t_{ij} = t_i + tg_{ij} + t_j} \tag{14}$$

$$\boldsymbol{t_i = 15 * \log\left(\frac{P_i}{10}\right)} \tag{15}$$

$$\boldsymbol{t_{ph} = u_i * t_p} \tag{16}$$

$$\boldsymbol{u_i = 1 + 0.1 * \max\left(0, tg_{ij} - T_{min}\right)} \tag{17}$$

$$\boldsymbol{t_p = \frac{T_{max}}{1 + \delta_i * e^{\left(-\rho_i * tg_{ij}\right)}}} \tag{18}$$

where F_{trans} is the cost per unit distance of the shortest travel mode; F_{rjgz} is the income per unit time of the travel subject; F_p is the cost of time required for fatigue recovery; d_{ij} is the mileage from city *i* to city *j*; t_{ij} is the shortest time cost from city *i* to city *j*; t_i and t_j is the travel

TABLE 7 Economic distance between cities after the opening of high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen
Nanchang	——	96.6	86.6	256.1	119.1	156.5	138.2	155.1	89.6	65.2	164.4
Yingtan	93.7	——	155.1	333.7	190.4	73.5	216.8	222.6	161.2	88.2	137.6
Jiujiang	83.6	156.4	——	287.7	187.4	179.8	188.3	220.3	143.7	131.2	89.9
Ganzhou	246.9	329	279.9	——	314.4	392	133.8	382.7	321.2	360.2	402.3
Yichun	113.5	187.6	182	314.4	——	250	233.5	51.1	43.8	162.8	325.5
Shangrao	153	73.7	178.7	398.7	254.4	——	276.8	282.5	220.5	161.9	100.7
Ji'an	134.8	217.4	186.2	136.5	238	276.9	——	269.8	207.9	152.2	296.4
Pingxiang	152.5	224.4	221.1	391.5	53.6	284.3	271.5	——	76.3	195.3	335.5
Xinyu	89.5	164.8	150.2	332.7	47.4	224.8	212.2	77.7	——	135.6	213.6
Fuzhou	59.7	84.8	125.4	358.2	162.2	155.6	146.2	189.6	128.7	——	149.7
Jingdezhen	163.1	142	92	420.1	346.2	103.3	293.2	344.1	211.8	162.7	——

time of city i and city j, respectively in urban areas; tg_{ij} is the travel time between city i and city j with the shortest time-consuming traffic mode; P_i is the total population of the urban area, the unit is ten thousand people; t_{ph} is the fatigue recovery time; u_i is the fatigue correction index of traffic mode i; t_p is the initial fatigue recovery time of vehicle i; T_{min} is the time when the fatigue of the traveler starts to gradually increase, and it usually takes a value of 3; T_{max} is the maximum value of the time required for fatigue recovery of the traveler, generally taken as 15; δ_i is to take traffic mode i, when $tg_{ij} = 0$ that is, the minimum time required to recover fatigue, δ_i using high-speed rail, general railway and highways, three modes of transport to take the value of 59, 45, and 48, respectively; ρ_i is the intensity coefficient per unit of recovery time, again taking values of 0.28, 0.35, and 0.33 for the three traffic modes, respectively.

R is the distance friction coefficient in Formula 8. To calculate easily, most researchers take r as 1 or 1, representing the state of economic connection between regional cities. However, this treatment only applies to the urban areas with excellent financial and homogeneity balanced development in east central China, with certain limitations. The unevenly developed Midwest region will cause errors in the gravitational calculation results. In this paper, the distance friction coefficient is defined as when there are high-speed railways, ordinary railways, and expressways in adjacent cities, the values are 2.00, 2.25, and 2.5, respectively; when cities are not adjacent, there are high-speed railways, ordinary railways, and expressways in adjacent cities, the values are 2.25, 2.50, and 2.75.

In order to observe more easily and intuitively the degree of economic linkages between cities along the route itself and other cities in the region, a study of economic linkage affiliation mode is referred to (Wang and Guan, 2018). The model is used to describe the share of the volume of economic linkages between two cities to explain their external radiation capacity. The calculation formula is shown in Formula 19:

$$M_{ij} = \frac{R_{ij}}{\sum_{j=1}^{n} R_{ij}} \tag{19}$$

where M_{ij} is the ratio of the volume of economic ties between city i and city j to the sum of economic linkages between city i and other cities, the larger M_{ij} is, the greater the impact of city i is by the economic connection of city j; $\sum_{j=1}^{n} R_{ij}$ is the sum of the amount of economic ties between city i and other cities.

2.4 Data sources

The above-mentioned coopetition relationship econometric model, the evaluation model of city-industry integration, and the improved economic gravity model rely on practical data for the computational solution. Therefore, in this paper, panel data of 11 cities along the high-speed railway in Jiangxi Province (Nanchang, Yingtan, Jiujiang, Ganzhou, Yichun, Shangrao, Ji'an, Pingxiang, Xinyu, Fuzhou, and Jingdezhen) are selected, and the data involved in the empirical study are obtained from the 2014–2018 Jiangxi Statistical Yearbook, the work reports of Jiangxi Provincial Government, the statistical yearbooks and statistical bulletins of each city, etc. Among them, travel time distances were obtained from railroad 12306.com, Gaode Map, and Ctrip.com. Some of the data were filled in by interpolation method to ensure completeness and validity.

3 Results

3.1 Evaluation of city-industry integration

According to the evaluation index system of city-industry integration constructed in section 1.2 and the index evaluation model of entropy weight method, the data are processed by Eqs 2, 3. Then the entropy of each index is derived according to Eq 4. After that, the weight value of each index is derived according to Eq 5, as shown in Table 1.

According to Eq 6, the data and weights of the corresponding indicators are multiplied to obtain each indicator's scores, which are summed up to the related system scores. Finally, the evaluation level of city-industry integration is the sum of all indicators' scores.

TABLE 8 Economic connections of 11 cities in Jiangxi Province before the opening of high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen	Total
Nanchang	——	5.05	17.25	0.42	5.03	2.87	1.2	0.65	2.15	13.72	0.27	48.61
Yingtan	5.19	——	3.57	0.37	1.18	21.94	0.98	0.64	1.42	2.1	1.09	38.48
Jiujiang	21.75	3.71	——	0.25	2.5	1.24	0.49	0.24	0.69	0.07	2.07	33.01
Ganzhou	0.7	0.51	0.33	——	0.09	0.16	7.4	0.05	0.08	0.06	0.03	9.41
Yichun	8.5	1.65	3.3	0.09	——	0.45	1.49	33.02	39.4	0.42	0.02	88.34
Shangrao	4.6	29.04	1.57	0.15	0.41	——	0.34	0.25	0.48	0.41	0.31	37.56
Ji'an	2.09	1.41	0.67	7.89	1.54	0.37	——	0.42	1.18	0.46	0.06	16.09
Pingxiang	1.11	0.89	0.32	0.05	32.93	0.26	0.41	——	4.19	0.05	0.05	40.26
Xinyu	3.57	1.94	0.89	0.08	38.61	0.49	1.12	4.07	——	0.19	0.16	51.12
Fuzhou	32.18	4	0.13	0.08	0.57	0.58	0.6	0.07	0.26	——	0.11	38.58
Jingdezhen	0.56	1.78	3.3	0.04	0.02	0.4	0.07	0.07	0.2	0.1	——	6.54

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TABLE 9 Economic connections of 11 cities in Jiangxi Province after the opening of high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen	Total
Nanchang	——	12.53	42.79	1.03	18.16	9.48	3.1	2.34	7.23	36.62	1.36	134.6
Yingtan	13.87	——	3.72	0.56	1.88	42.38	1.11	1.02	1.9	2.1	2	70.54
Jiujiang	51.8	3.98	——	0.75	6.95	6.82	1.47	1.01	0.69	2.55	5.06	81.08
Ganzhou	1.41	0.71	0.89	——	0.56	0.31	10.28	0.28	0.37	0.06	0.17	15.04
Yichun	26.01	2.44	8.49	0.57	——	0.83	3.33	68	83.56	0.42	0.02	193.67
Shangrao	13.78	56.63	8.5	0.33	0.85	——	0.56	0.53	0.83	0.41	11.46	93.88
Ji'an	4.96	1.61	2.02	11.85	3.72	0.61	——	2.27	3.46	0.46	0.31	31.27
Pingxiang	3.72	1.49	1.36	0.32	72.82	0.57	2.27	——	8.63	0.92	0.05	92.15
Xinyu	11.85	2.86	0.89	0.45	89.68	0.94	3.59	8.85	——	2.02	0.16	121.29
Fuzhou	77.78	4	4.46	0.08	0.57	0.58	0.6	1.14	2.47	——	0.11	91.79
Jingdezhen	2.73	3.56	8.4	0.24	0.02	15.47	0.41	0.07	0.2	0.1	——	31.2

10.3389/fenvs.2023.1082664

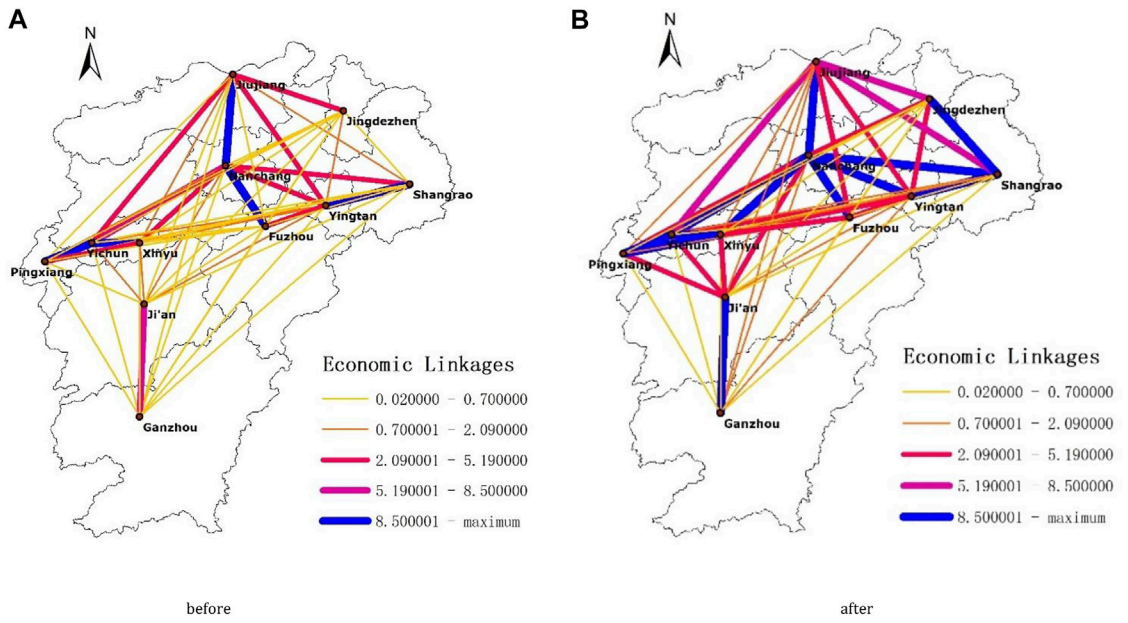

FIGURE 1
Economic linkages change before **(A)** and after **(B)** opening high-speed rail.

Combining the Formula and Table 1 with the relevant data of each city in Jiangxi Province, the degree of city-industry integration in 11 cities along the high-speed railway in Jiangxi Province is calculated and obtained, as shown in Table 2.

3.2 The impact of coopetition relationship on city-industry integration

3.2.1 Model specification test

Since the panel data has time and monomer data characteristics, the model setting of the panel data should be confirmed. In this paper, we choose the redundant variable test method of the double fixed effect model and use STATA to calculate and test whether the time and monomer dimensions of the panel data exist to confirm the model set. The test results are shown in Table 3.

As can be seen from Table 3, both time and single-unit effect tests are significant, and both F-values and chi-square values pass the test at the 1% significance level. That means the collected panel data have both time and single-unit dimensions.

3.2.2 Analysis of model results

Since the panel data have both time and single dimensions, both of them should be taken into consideration in the setting of the coopetition relationship model. Using a fixed-effects model with Stata software, the calculated result data are shown in Table 4.

As seen from Table 4, the overall estimated fit of the model is better, and all are more significant, indicating that the model has good explanatory power.

It can be seen from Table 4 that fixed investment (*FI*) and labor force growth (*LG*) are the two explanatory variables representing the regional competitive relationship. The fitted coefficients of fixed investment (*FI*) in all three models are significantly positive (0.18, 0.33, and 0.43) and conform to the 5% significance level, indicating that investment volume can enhance the development of city-industry integration in this city. The appropriate coefficients of its spatial lag term (*SL_FI*) in both the time and single-unit fixed effects models are negative (−0.85, −0.81, and −1.27), indicating that the competitive behavior of cities in response to investment will hurt the development of city-industry integration in the remaining cities. The fitted coefficients of labor force growth (*LG*) are 0.18, 0.21, and 0.21, respectively, which show that labor force growth can effectively enhance the development of city-industry integration in this city. Still, the fitted coefficients of its spatial lag term (*SL_LG*) are −0.23 and −0.16 in the single and double fixed effect models, respectively, which means that the labor force growth in this city will inhibit the development of city-industry integration in the remaining cities. In a nutshell, the explanatory variables with competitive attributes in the cooperative characteristics of city coopetition will negatively affect the outcome variable of city-industry integration in other cities and positively affect themselves.

The level of industrial concentration (*IC*) and the level of human capital mobility (*HCM*) are the two explanatory variables representing the regional cooperation relationship. The values *ZY* are 1.55, 1.35, 1.55, and the corresponding spatial lag term (*SL_HCM*) in the time and double fixed effect models are 0.77 and 0.98, respectively. That indicates the level of industrial concentration can significantly enhance the development of city-industry integration in this area and will promote the development of city-industry integration in the rest of the cities. The fitted coefficients *HCM* are all positive at the 5% significance level, but its corresponding spatial lag term (*SL_HCM*) is not significant in each model, which confirms that the level of human capital mobility can effectively enhance the development of city-

TABLE 10 Economic affiliation of cities before opening high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen
Nanchang	——	10.39%	35.49%	0.86%	10.35%	5.90%	2.47%	1.34%	4.42%	28.22%	0.56%
Yingtan	13.49%	——	9.28%	0.96%	3.07%	57.02%	2.55%	1.66%	3.69%	5.46%	2.83%
Jiujiang	65.89%	11.24%	——	0.76%	7.57%	3.76%	1.48%	0.73%	2.09%	0.21%	6.27%
Ganzhou	7.44%	5.42%	3.51%	——	0.96%	1.70%	78.64%	0.53%	0.85%	0.64%	0.32%
Yichun	9.62%	1.87%	3.74%	0.10%	——	0.51%	1.69%	37.38%	44.60%	0.48%	0.02%
Shangrao	12.25%	77.32%	4.18%	0.40%	1.09%	——	0.91%	0.67%	1.28%	1.09%	0.83%
Ji'an	12.99%	8.76%	4.16%	49.04%	9.57%	2.30%	——	2.61%	7.33%	2.86%	0.37%
Pingxiang	2.76%	2.21%	0.79%	0.12%	81.79%	0.65%	1.02%	——	10.41%	0.12%	0.12%
Xinyu	6.98%	3.79%	1.74%	0.16%	75.53%	0.96%	2.19%	7.96%	——	0.37%	0.31%
Fuzhou	83.41%	10.37%	0.34%	0.21%	1.48%	1.50%	1.56%	0.18%	0.67%	——	0.29%
Jingdezhen	8.56%	27.22%	50.46%	0.61%	0.31%	6.12%	1.07%	1.07%	3.06%	1.53%	——
Affiliation	223.39%	158.59%	113.68%	53.22%	191.71%	80.41%	93.57%	54.13%	78.41%	40.98%	11.92%

industry integration in this city, but has no significant impact in the rest of the cities in the region. In conclusion, explanatory variables with cooperative attributes in the cooperative characteristics of city competition will have a positive or non-significant effect on the outcome variable of city-industry integration in other cities and a positive effect on itself.

3.3 Analysis of high-speed rail effect on the cities' economic cooperation

According to Eq. 9 and Table 2, the gravitational index K_{ij} of city *i* under city *j* can be calculated, as shown in Table 5. Combining Eqs 10–18, we calculated the economic distance D_{ij} between cities without and with the opening of high-speed rail, as shown in Tables 6, 7.

Those tables show a difference in the high-speed rail opening effect on the economic distance of cities along the route. The economic distance between cities reflects the transportation travel costs, which are positively correlated with each other. High-speed rail increases regional accessibility between cities, thus reducing time costs and facilitating economic interactions. In addition, it has a significant impact on passenger flows, accelerating the crowd concentration effect and increasing the share of employment in secondary and tertiary industries (Cai et al., 2022). As a transportation hub city in the province, Nanchang has relatively fewer transportation travel costs affected by the effect of high-speed rail. For cities such as Yingtan, Jiujiang, Yichun, Shangrao, Pingxiang, Ganzhou, Ji'an, and Xinyu, the transportation cost of residents has increased after the opening of high-speed rail. The reason is that residents in these cities have relatively low incomes and pay more attention to the economy of travel modes than the time cost. After the opening of high-speed rail,

TABLE 11 Economic affiliation of cities after the opening of high-speed rail.

	Nanchang	Yingtan	Jiujiang	Ganzhou	Yichun	Shangrao	Ji'an	Pingxiang	Xinyu	Fuzhou	Jingdezhen
Nanchang	——	9.31%	31.79%	0.77%	13.49%	7.04%	2.30%	1.74%	5.37%	27.21%	1.01%
Yingtan	19.66%	——	5.27%	0.79%	2.67%	60.08%	1.57%	1.45%	2.69%	2.98%	2.84%
Jiujiang	63.89%	4.91%	——	0.93%	8.57%	8.41%	1.81%	1.25%	0.85%	3.15%	6.24%
Ganzhou	9.38%	4.72%	5.92%	——	3.72%	2.06%	68.35%	1.86%	2.46%	0.40%	1.13%
Yichun	13.43%	1.26%	4.38%	0.29%	——	0.43%	1.72%	35.11%	43.15%	0.22%	0.01%
Shangrao	14.68%	60.32%	9.05%	0.35%	0.91%	——	0.60%	0.56%	0.88%	0.44%	12.21%
Ji'an	15.86%	5.15%	6.46%	37.90%	11.90%	1.95%	——	7.26%	11.06%	1.47%	0.99%
Pingxiang	4.04%	1.62%	1.48%	0.35%	79.02%	0.62%	2.46%	——	9.37%	1.00%	0.05%
Xinyu	9.77%	2.36%	0.73%	0.37%	73.94%	0.78%	2.96%	7.30%	——	1.67%	0.13%
Fuzhou	84.74%	4.36%	4.86%	0.09%	0.62%	0.63%	0.65%	1.24%	2.69%	——	0.12%
Jingdezhen	8.75%	11.41%	26.92%	0.77%	0.06%	49.58%	1.31%	0.22%	0.64%	0.32%	——
Affiliation	244.19%	96.10%	65.08%	41.84%	181.41%	124.54%	81.44%	56.25%	73.80%	11.63%	23.72%

Fuzhou, and Jingdezhen residents' transportation travel costs have decreased because the geographical distance between these cities and some cities is shorter, and the original transportation travel costs are more diminutive. At the same time, the opening of some high-speed rail lines did not significantly increase the cost of travel between the two cities but shortened the travel time.

According to Eq 8, find the specific value of the two corresponding economic linkages, which reflects the influence among the cities before and after the opening of high-speed rail. Then, the city-industry integration assessment value was multiplied by 1,000 to facilitate observation, and the calculation results are shown in Tables 8, 9.

The gravity model calculation determines the volume of economic linkages between cities in Jiangxi Province. The results are mainly influenced by the degree of city-industry integration and economic distance. The data in Tables 8, 9 are compared to observe the changes in the economic linkage volume after the opening of the high-speed railroad. Meanwhile, to show the differences more visually, this paper utilizes ArcGIS to map the volume of urban economic linkages based on the data in Tables 8 and 9, which indicates the economic linkage by connecting each city's center points with the line segment's color and thickness. When the volume of economic linkage between two cities is greater, the line is thicker and darker. And the results in a) and b) are in Figure 1 below.

Figure 1A shows the situation before the opening of high-speed railroad lines. Jiangxi province could be divided into Nanchang-Jiujiang-Fuzhou urban agglomeration, Yingtan-Shangrao urban agglomeration, Pingxiang-Xinyu-Yichun, and Ji'an-Ganzhou urban agglomeration. Since Nanchang is a provincial capital city, its economic linkages with other urban agglomerations are more notable in terms of volume. However, the economic linkages between other regions were weak, mostly less than 2.09. The economic linkages among the urban agglomerations led by Ji'an and other regions were less than 0.7, forming a more isolated part of Jiangxi province in Figure 1A. Figure 1B shows that the economic linkages among urban agglomerations have significantly enhanced after the opening of high-speed railroad lines. It performs a trend of mutual integration and outward expansion. In the Yingtan-Shangrao urban agglomeration, the amount of economic linkages among Jingdezhen, Yingtan, and Shangrao increased significantly after the opening of the high-speed railroad. And a new urban agglomeration is formed by these three cities. At the same time, the Nanchang-Jiujiang-Fuzhou urban agglomeration is led by the provincial capital. Nanchang, the capital of Jiangxi province, has greater economic linkages with the surrounding urban agglomerations, and its core position in the area is more solid. In addition, in the Yichun-Pingxiang-Xinyu urban agglomeration, the economic linkage between Pingxiang and Xinyu has been enhanced, and the urban agglomeration Ji'an-Ganzhou City in the south is connected as a link in the central part of Jiangxi Province.

According to Tables 8, 9, and Eq 19, the affiliation degree of economic linkages of 11 cities in Jiangxi Province before and after opening high-speed rail is calculated. The top three cities in terms of economic affiliation are shown in Tables 10, 11.

4 Conclusion

From the perspective of city-industry integration, an economic gravity model and a coopetition relationship econometric model are constructed to analyze the urban agglomeration structures in the province and their changing trends under the influence of high-speed rail. Moreover, it is important for evaluating different economic variables to suppress unhealthy competition and promote cooperative development of urban agglomerations. Developing high-speed rail networks can promote the prosperity and vitality of cities. In this paper, based on the panel data of cities in Jiangxi Province and the relative attributes of transportation, the evaluation model of city-industry integration, the econometric model of the coopetition relationship, and the economic linkage gravity model are constructed, respectively. Then, cities' economic linkage and affiliation are analyzed, and the influence mode of the coopetition relationship variables in the city-industry integration is analyzed. The results are shown as follows:

1) Different economic variables of one city affect neighboring in different ways under the coopetition relationship. Substituting each variable into the time-fixed model, single-fixed model and double-fixed model, the fitting coefficients of the fixed investment (*FI*) and labor force growth (*LG*) variables into these three models are positive, while their spatial lagged terms (*SL_FI*) and (*SL_LG*) are negative in these three models, respectively. This indicates that their improvement is beneficial to their own city-industry integration development, but the growth of these two indicators inhibits the growth of other cities. In addition, the fitted coefficients of industrial concentration level (*IC*) and its spatial lag term (*SL_IC*) are positive in all three models, indicating that its increase can promote the development of city-industry integration in this city and other cities at the same time. Although the level of human capital mobility (*HCM*) can significantly enhance the development of its own city-industry integration, it does not noticeably affect other cities. In total, it can be concluded that reducing the growth rate of fixed capital investment and labor force while accelerating the process of industrial centralization is conducive to suppressing the competitive relationship of urban agglomerations and reinforcing their cooperative relationship.

Why does an increase in two explanatory variables, investment (*FI*) and labor force growth (*LG*), lead to a lower level of city-industry integration in other cities? The reason may be as follows: within an urban agglomeration, the overall investment is relatively limited. When the fixed investment is given to one of the cities, the other cities have less, thus showing a competing pattern. At the same time, an increase in foreign direct investment leads to a "crowding-out effect" that reduces firms' capacity in neighboring cities, a result similar to García's findings (García et al., 2013).

The labor force growth can be broadly divided into two areas: the native-born labor force and the migrant labor force. For cities in the center of urban agglomerations, although the local population growth is limited, it can attract the employment of migrant workers from neighboring cities and promote labor mobility and settlement there. In the regional competition, the increase of the mobile labor force will boost the local government to respond to labor demand and thus increase the proportion of public welfare spending on people's livelihoods (Yang et al., 2019), which will further enhance the city-industry integration in this city. An urban agglomeration has limited labor force growth, and the labor force tends to go to cities with more job opportunities and more developed industrial structures for employment. In contrast, fewer job opportunities exist for regions with more backward economic development.

Hence, a higher labor force growth in one city means that other cities will be limited. The relatively low labor force growth will further reduce city-industry integration. The reduction in travel time costs due to the opening of high-speed rail and the concomitant increase in industrial concentration, which in turn leads to further development of the city's economic level (Junius, 1997), reduces the income gap between regions (Yang et al., 2022).

2) The high-speed rail opening can enhance the economic connection among cities. The continuous expansion of the high-speed railway network in Jiangxi province reduced the average economic distance between cities from 1946.10 to 1839.59, which caused a significant increase in the level of city-industry integration development in each city. With the development of high-speed railroads, the average amount of economic linkages between cities increases from 37.09 to 86.96, reflecting the significant effect of high-speed railways on the amount of economic linkages. The financial affiliation of cities is calculated based on the economic linkage data. The construction of high-speed rail lines will cut the economic distance between places and strengthen economic ties among urban agglomeration.

In addition, constructing the high-speed rail network can enhance the connection among urban agglomerations. For the urban agglomerations that were previously not closely connected economically, one or several more connected cities will be used as hubs on the original basis. The economic connection of non-closely related areas will be improved, and this situation will enhance the central position of the hub city in the urban agglomeration. Since Ji'an and Ganzhou are located in the southern region of Jiangxi Province, their relative independence in terms of economic linkages is highlighted even more. However, with relevant high-speed rail facilities opening, Ji'an has shown an increase in economic linkages to neighboring urban agglomerations since its proximity to Pingxiang and Xinyu cities. Therefore, it can be considered a hub to bridge the urban agglomeration in the north and south of Jiangxi Province.

3) The high-speed rail opening can strengthen the affiliation of the major city, and facilitating the new central city. According to the degree of economic affiliation, there are four major economic development regions in Jiangxi Province: ① the Nanchang-Jiujiang-Fuzhou urban agglomeration; ② the Shangrao-Yingtan-Jingdezhen urban agglomeration; ③ the Pingxiang-Yichun-Xinyu urban agglomeration; ④ the Ganzhou-Ji'an urban agglomeration. Those financial centers are Nanchang, Shangrao, Pingxiang, and Ganzhou. Among them, Nanchang, as the capital city of Jiangxi Province, has a high economic and political status. According to the results of Section 3.3, Nanchang's affiliation degree from other cities increased from 223.39% to 244.19% after the opening of the high-speed railway. It proves that Nanchang's radiation capacity has increased, and its status as a central city in Jiangxi province is becoming more solid. It has formed a form of multi-urban agglomerations grouping and radiating to the central cities of each other, with Nanchang as the center of gravity.

Besides, the construction of high-speed rail can promote the creation of the central city of the urban agglomeration. The most typical case is "Shangrao-Yingtan-Jingdezhen," located in the eastern part of Ganzhou. Before the high-speed railway's opening, the cluster's central city was Yingtan. Still, after the start of the high-speed railway, Shangrao became the most affiliated city and became the new major city. This phenomenon might be because the economic gap between the two cities was not so large before. And after the high-speed rail opening, one of them rapidly developed with its better location.

5 Limitations and recommendation

However, this study also has certain limitations that can be considered for future research. On the one hand, the city distance one value in the gravity model only feels the fastest single transportation mode between cities, which means that the transit time between different transportation modes and the economic cost of additional transportation options are not considered. This aspect may affect the travel choice of passengers between cities that are far away and have not yet opened high-speed rail. On the other hand, the city-industry integration evaluation system does not consider the influence caused by political and cultural factors. However, different countries and regions have different levels of economic development, so their context-specific considerations need to be considered. Future research can be improved in the following way. Firstly, the study can be improved by selectively adding some indicators about specific cultural industry or policy, and recalculate the weight of indictors. Secondly, future research can complicate the distance friction coefficient or the attraction index in a more complex function expression, which can efficiently describe the transit among different transportation.

According to the results of the paper, there are some recommendations for urban agglomeration in Jiangxi Province. On the one hand, cooperation with neighboring cities is strengthened according to the urban agglomerations' geographical location and original industrial structure. In turn, it will form compatible urban agglomerations in the region and achieve differentiated development within the agglomerations. Cities with a lower degree of city-industry integration should take the initiative to undertake industrial transfer and appropriately transfer population, resources, technology, and other industrial factors to those cities with lower city-industry integration. And cities with a higher degree of city-industry integration have to focus on developing "cutting-edge" industries and form a reasonable division of labor in regional industries. Furthermore, the cooperation and exchange within each urban agglomeration should be strengthened, the construction of high-speed rail should be reasonably planned, the scale of the high-speed rail network should be expanded, and the connection of transportation infrastructure should be improved. That would realize the sharing of public services of cities within the region and enhances the overall degree of city-industry integration of urban agglomerations. Finally, to avoid vicious competition, the cooperation circulation of human capital should be strengthened between each urban agglomeration group through the enhancement of high-speed railway accessibility that would promote the high-frequency exchange and interaction of high-level talents. At the same time, attention should be paid to the reasonable distribution of fixed investment in each urban agglomeration to avoid the reduction of the overall degree of city-industry integration development of urban agglomerations due to over-concentration.

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

ZT: validation, supervision, funding acquisition, review; HB: methodology, formal analysis, writing-original draft, writing-review, editing, data curation; JS: data curation, editing; YX: Methodology, Empirical model estimation; ZW: data curation, editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

YX was employed by China Railway Nanchang Group Co., Ltd. ZW was employed by Wuhan Metro Operation Co.

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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Exploring the impact of the digital economy on green total factor productivity in China: A spatial econometric perspective

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The digital economy is considered a driving force of green economic development. However, only a few studies have examined the relationship between the digital economy and green total factor productivity (GTFP). According to the principal component method and super-efficient Slacks-based measure model, the digital economy level and green total factor productivity GTFP were measured for China's provinces based on panel data from 2013 to 2019. The spatial econometric model was then used to analyze the effects of the digital economy level on green total factor productivity GTFP. Results showed that the overall level of green total factor productivity GTFP maintained a steady growth trend, with an average yearly growth of 4.19%. Significant regional differences reflecting the development characteristics of eastern, central, and western regions were also observed. Most provinces showed either high or low values of both green total factor productivity GTFP and digital economic development thereby revealing spatial heterogeneity for the different provinces and cities. The spatial Durbin model showed that the digital economy had a significant direct effect (0.1498) and spatial spillover effect (0.3438) on green total factor productivity GTFP, the latter being greater than the former, with this conclusion supported by the robustness test. Technological innovation positively regulates the contribution of the region's digital economy to green total factor productivity GTFP and negatively regulates the spatial spillover of the digital economy to green total factor productivity GTFP in neighboring regions.

KEYWORDS

spatial heterogeneity, green total factor productivity, spatial measurement, moderating effect, SBM

1 Introduction

With the increasingly strict constraints on the ecological environment, economic development needs to proceed in a green and high-quality direction to reduce both resource and environmental loss. The green total factor productivity (GTFP) is the core indicator to measure the high-quality development of the economy by considering the "undesired output" problem of production activities. Taking economic growth and environmental protection into account, and under resource loss and environmental protection constraints, improving green total factor productivity GTFP to encourage the rational and efficient allocation of resources is necessary to realize green development. In this context, the digital economy provides a feasible path for dealing with environmental conservation issues. The extensive integration of the real economy and the digital economy has contributed significantly to the new development pattern of "dual circulation," which will help Chinese enterprises transform and upgrade to sustainable production methods, such as low-carbon, symbiotic, and green methods. Thus, the environmental benefits of the digital economy should also be considered. In its 19th National Congress, the Communist Part of China also vehemently advocated for advancing the digital economy and considered it a predominant approach to developing a green economy. Hence, it makes sense to study how the digital economy affects GTFP and discuss how the China's GTFP is progressing.

The GTFP integrates both economic benefits and the protection of ecological resources. Compared with total factor productivity (TFP), which accounts only for the input restraints of labor and capital, GTFP also considers the restraints of the environment and resources. In the measurement of GTFP, Pittman (1983) firstly incorporated environmental pollution into the economic model, and applied the data envelopment analysis approach to investigate undesired output. Later, researchers introduced the directional distance function and the Malmquist–Luenberger index, which expanded the method for the simultaneous estimation of multiple outputs and inputs to better fit the constraints of the environment and resources on the production process (Chung et al., 1997; Oh, 2010). Aparicio et al. (2017) used Malmquist–Luenberger index to evaluate GTFP from 1995 to 2007 and reported that technological progress was increasing, while technological efficiency declined rapidly, indicating the GTFP's stagnation. Chen and Golley (2014) calculated the changing pattern of GTFP, and considered carbon dioxide emissions as the undesired output. Research has also focused on how various input factors affect GTFP, including economic factors (Zhou Y. Y. et al., 2019), trade cooperation (Zhao P. J. et al., 2020; Xie and Zhang, 2021), government regulations (Li and Wu, 2017), and technological innovation (Wang M. L. et al., 2021), among others. For instance, Li and Liao (2020) analyzed data of 40 countries obtained from 1991 to 2014, betwixt financial advancement and GTFP, a reverse U-shaped relationship exists. Cao and Wang (2017) reported that foreign trade could promote an increase in GTFP through developing (R&D) investment and improving labor levels. Zhou Y. et al. (2019) proposed that China's foreign direct investment enhances the green economy in provinces. Wu et al. (2020) stated the mutual effect of government and environmental decentralization generates a "race to the bottom" effect, meanwhile, the environmental dispersion on the effectiveness of regional green growth has been gradually decreasing.

Few studies have directly and systematically evaluated the overall impact of the digital economy on GTFP, with the majority of them focused on the internet and information technology. Researchers have highlighted that information technology can improve labor productivity (Vu, 2013) and promote economic growth (Madden and Savage, 2000), to which GTFP is positively correlated. Niebel (2018) identified that ICT capital exerts a positive effect on gross domestic product (GDP) growth using various panel data regressions. Nguyen et al. (2020) proposed that ICT and financial development are effective stimuli of positive drivers of economic growth. Some researchers started by reducing environmental pollution and expenditure of energy (Gong et al., 2020). Moreover, according to Wu et al. (2021), the internet indirectly affects regional GTFEE by promoting regional innovation capabilities and by decreasing the degree of resource misallocation. Vidas-Bubanja (2014) stated the potential of the digital economy to enhance sustainability by making production and life more energy efficient. Meanwhile, the feasibility of sustainable development can be enhanced by the integration of the green and digital economies, while technological innovation can provide powerful solutions to climate change and environmental challenges. However, the ICT industry is not entirely ecologically friendly (Zhou X. et al., 2019). For example, the communications industry is energy-intensive, and the manufacturing, use, and disposal of related goods also requires a significant amount of energy (Salahuddin and Alam, 2015). Therefore, some researchers have proposed that ICT has a non-linear relationship with GTFP. Li et al. (2020) proposed that internet growth exerted a non-linear impact on China's GTFP, and when human capital levels consistently exceeded a threshold, the influence shifted from weakly negative to positive.

In summary, although the existing literature on both digital economy- and GTFP-related content is extensive, only a few studies discussed how the former affects GTFP by being a new impetus for economic development (Han et al., 2022; Wang J. et al., 2022; Yang et al., 2022). However, Han et al. (2022) concentrated on how digital economy affects carbon reduction, and overlooked economic growth. Whereas, Yang et al. (2022) and Wang J. et al. (2022) did not consider geographical elements in support of panel regressions and non-spatial panels. Meanwhile, most prior studies considered the mechanisms of

industrial transformation, human capital, and environmental regulation (Gu et al., 2022; Liu et al., 2022; Lyu et al., 2022). Technological innovation is the primary driver of economic growth and the digital economy. Nevertheless, its moderating impact on environmental effects of the digital economy has been neglected in previous studies (Luo et al., 2022). Moreover, the digital economy involves multiple fields and spans multiple industry sectors, hence there is no unified quantitative indicator that can be employed to assess it. Based on this, the present study explored how the digital economy affects GTFP from both theoretical and empirical perspectives. First, a theoretical framework was constructed for the digital economy and GTFP, and suggested corresponding theoretical assumptions and established an index system. The digital economy was evaluated using the principal component method. Quantitative processing was then conducted to provide a basis for discussion of: 1) the mechanism by which the digital economy affects GTFP; 2) the regulatory roles of technological innovation; 3) the effective path for the digital economy to promote GTFP.

This study provides the following marginal contributions: Firstly, the digital economy was evaluated from four dimensions: digital innovation, digital industrialization, digital infrastructure and industrial digitization; to provide a reference for digital economy-related measurements. Secondly, the model incorporated spatial elements to discuss the spatial effect of the digital economy on GTFP. Finally, a consideration of how technological innovation impacts the influencing mechanism of the digital economy on GTFP is made. The rest of this paper is organized as follows. In section 2, the theoretical mechanism and assumptions are described, in section 3 the measurement system and data used are presented, section 4 interprets the findings of the empirical analysis model, and in section 5 conclusions and recommendations are suggested.

2 Theoretical hypotheses

2.1 Linear effect of the digital economy on GTFP

The essence of the digital economy is that data is the core production factor and it promotes the innovation of production means to propels the green economic transformation (Ma and Zhu, 2022). The digital economy influences GTFP through scale effect, technology effect, and structural effect. As for the technology effect, the digital economy is a type of technological innovation. Its high-tech characteristics can promote the sharing of information resources to overcome the original spatial constraints of the industry, realize the precise connection of resources, and allow information technology to penetrate industrial circulation, improve overall production efficiency (Chen et al., 2019), and reduce resource misallocation (Berrone et al., 2013). Regarding scale effect, the expansion of emerging industries is driven by the digital economy, which gives rise to more talent, technological, and knowledge-based growth points in the emerging economy, realizes the industrial aggregation of the emerging economy, and promotes TFP improvement. In addition, in terms of structural effects, which can encourage dynamic change and empower green development with digital technology (Wang L. et al., 2021). The utilization of high-tech artificial intelligence has enhanced production processes by transforming and upgrading traditional industries as well as setting new industries and formats to achieve high output with low pollution and low input. Meanwhile, high-tech artificial intelligence can help drive technological innovation and resource utilization efficiency within the digital economy so it develops industry from mid-to-high end (Wang J. et al., 2022), thereby improving the GTFP. Thus, the following hypothesis was proposed:

Hypothesis 1: The digital economy has a positive effect on GTFP.

2.2 The regulating effect of technological innovation

Green development cannot be separated from the harmonization of social, economic, and ecological dimensions, which includes resource utilization and economic development, and technological innovation has emerged as an indispensable means of balancing ecological friendliness and economic expansion. The digital economy encourages GTFP growth that relies on technological innovation development (Hao et al., 2022). Firstly, innovative information technology expands the digital economy's development opportunities and competitive advantages, guarantees that green technology innovation is carried out in the digital environment, eliminates the technology gap limitation (Lu and Zhu, 2022), expedites the conversion of digital technology achievements to economic benefits, and encourages green economic development (Wang X. et al., 2022). Secondly, technological innovation can support the creation and use of products for the digital economy, advance production, energy-saving, and environmental protection technologies, and effectively optimize front-end production and end pollution treatment technologies of businesses (Li and Lin, 2017). It can also enhance production technology and pollution management in the industry and promote the entire industry to progress from primitive to technologically advanced. The endogenous growth theory assumes that increasing production efficiency requires technical advancement and the growth of strategic emerging industries and new energy (Liu and Dong, 2021). Technological advancement reduces the reliance on natural resources for urban development (Miao et al., 2017), enables enterprises to develop a variety of clean energy sources (Chen, 2022), replaces polluting energy sources, improves energy utilization, modifies the structure of energy use, accelerates the transition of highly

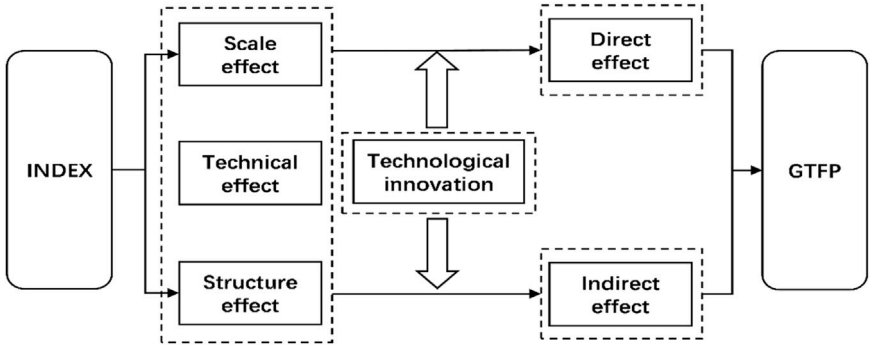

FIGURE 1
Theoretical mechanism model.

polluting and energy-consuming enterprises to green and low-carbon operations, and subsequently reduces pollution.

Concurrently, there is a spillover of technological innovation, which may have a suppressive impact on the GTFP of nearby regions (Wang H. et al., 2021). It is likely that technological advancements could have a "siphon effect" (Sun, 2022) that attracts the migration of high-tech industries and enterprise personnel from neighboring regions. This results in the outflow of talent and resources from neighboring regions, and thereby suppresses the development of GTFP in neighboring regions. Additionally, environmental control standards rise in tandem with the advancement of green technology. This results in the relocation of companies that are highly polluting or with outdated production capabilities to the periphery of the region (Zhao H. et al., 2020). This creates a "polluters paradise" in neighboring regions and impedes their GTFP growth and green transformation. According to the above findings, the following hypotheses were proposed:

Hypothesis 2: Technological innovation enhances the positive impact of the digital economy on local GTFP.

Hypothesis 3: Technological innovation negatively regulates the spatial spillover effect of the digital economy on neighboring regions' GTFP.

Based on the above research assumptions, Figure 1 displays the theoretical mechanism model of our research.

3 Materials and methods

3.1 Construction of the indicator system

The digital economy is an extension of the concept of the internet economy within the information economy. It is a new type of business involving many subjects and is not restricted to any specific industry. Industrial digitization, industrialization, digital infrastructure and digital innovation were used to construct our digital economy evaluation system (Table 1). Digital infrastructure lays the basis for the digital economy, and the improvement of basic facilities directly determines the level of hardware facilities in the digital economy. Whereas, digital industrialization and industrial digitization are the core of the development of the digital economy, The primary driving force behind the digital economy is R&D innovation, which guarantees economic long-term sustainability.

3.2 Research methods

3.2.1 Super-efficient slacks-based measure (SBM)

The principle of the model is as follows:

$$\min \rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{ik}}}{1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{S_r^+}{y_{rk}} + \sum_{t=1}^{q_2}\frac{S_t^{b-}}{b_{tk}}\right)}$$

$$s.t.\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - S_i^- \le x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + S_r^+ \ge y_{rk} \\ \sum_{j=1,j\neq k}^{n} b_{tj}\lambda_j - S_t^{b-} \le b_{tk} \\ \lambda, S^-, S^+ \ge 0 \\ i = 1,2,\cdots,m; r = 1,2,\cdots,q_1; \\ t = 1,2,\cdots,q_2; j = 1,2,\cdots,n(j \neq k) \end{cases}$$

where q_1 and q_2 are the numbers of desired and undesired output indicators, respectively; m is the number of input indicators; ρ is spatial autoregressive coefficient value; λ is the weight vector; and S_i^-, S_r^+, and S_t^{b-} are the slack variables for input, and desired and undesired outputs, respectively. Particularly, when ρ = 1 and S_i^-, S_r^+, and S_t^{b-} are all 0, the decision-making unit (DMU) is valid;

TABLE 1 Digital economy indicator system.

Primary indicator	Secondary indicator
Digital infrastructure	Cable density
	Mobile phone switching capacity
	Number of pages
	Number of internet broadband access ports
	Mobile phone penetration
Digital industrialization	Enterprise fixed asset investment in software, information transmission and information technology service industry/fixed asset investment in the whole society
	Total telecom business
	Total postal service
	Software business revenue
Industrial digitalization	New product sales revenue of industrial enterprises above designated size
	Proportion of companies with e-commerce activities
	E-commerce transaction volume/added value of the tertiary industry
	Digital finance
	Industrial added value
Digital innovation	Full-time equivalent of R&D in enterprises above designated size
	R&D personnel of enterprises above designated size
	Technology market turnover/GDP
	Number of patent applications

then when $0<\rho<1$, the current evaluation DMU is invalid; when $\rho > 1$, the current evaluation DMU is efficient.

3.2.2 Spatial Durbin model

Spatial Durbin model measures the influence on the region and adjacent regions, and has been commonly employed in practice (Liu and Song, 2020; Wang H. et al., 2021; Wu et al., 2021; Zhao and Wang, 2022), The equation is given below.

$$Y = \rho WY + X\beta + \theta WX + \varepsilon$$

where β and θ are the parameters to be estimated; X and Y are explanatory and explained variables respectively; then ρ is the spatial autoregressive coefficient; W is the spatial 0–1 weight matrix selected for this study, meaning that if two provinces are adjacent $W_{ij} = 1$, otherwise $W_{ij} = 0$; and ε is a random disturbance term.

3.3 Variable setting

3.3.1 Explained variables

GTFP (GTFP):By employing the perpetual inventory method (Hao et al., 2020), in this study the SBM model was used to estimate the number of employees as labor input, and energy input as total energy consumption. The constant GDP represented the desired output. The three industrial wastes—industrial wastewater chemical oxygen demand, industrial waste gas SO_2, and industrial waste generation—represented undesired output.

3.3.2 Core explanatory variable

Digital economy (INDEX): Calculated using the principal component method in accordance with the index system constructed as explained in section 3.1.

3.3.3 Control variables

Economic development level (PGDP): Economic growth is intimately related to environmental quality. Utilizing the *per capita* gross regional product to evaluate PGDP (Zheng et al., 2022).

Financial development level (FINANCE): Financial development can alleviate the financing constraints encountered by enterprises while engaging in R&D innovation, release the vitality of enterprises' industrial technological innovation, and provide capital power for the improvement of GTFP. This indicator was measured using the financial institutions' loan-to-deposit ratio at the end of the year (Huang et al., 2014).

Environmental regulation (ENV): High-quality development cannot be achieved without the pushback effect of environmental regulation on economy, which can control the entry and expansion of high-polluting industries and enhance high-quality development. This indicator was measured by the ratio of government environmental protection expenditure to financial expenditure (Guo, 2019).

Foreign investment (FDI): The introduction of foreign capital results in management experience and technology spillover through the "demonstration effect" and "diffusion effect." This can enhance industry productivity and drive urban economic development. The resource environment increases pressure and reduces the GTFP. This indicator was determined using the percentage of foreign investment in the GDP (Li et al., 2021).

Human capital (EDU): High-quality human capital is conducive to innovative R&D, can foster greater innovation development in the area, and is an essential driver for transforming the economic model. This indicator was measured by using the average years of education (Qiu et al., 2021).

3.3.4 Adjustment variables

Technological innovation (TECH): Technology innovation is essential to the economic transformation of China, promoting the creation and application of green Frontier technologies, as well as lowering manufacturing costs and increase industrial added value. This indicator was measured by weighted patents (Chen et al., 2022), more specifically, the number of weighted patents = the number of inventions obtained in the year × 0.5 + the number of utility models obtained in the year × 0.3 + the number of designs obtained in the year × 0.2. The data were collected from "the China Science and Technology Statistical Yearbook."

3.4 Data sources

The data used in this study were panel data of 30 provinces (excluding Tibet, Hong Kong, Macao, and Taiwan). The data were collected from 2013 to 2019. The linear imputation method was utilized to replenish the missing data.

4 Results and discussion

4.1 Analysis of China's GTFP

Overall, China's GTFP value for the 2013–2019 period was low (Figure 2), demonstrating that the economy was extensively growing and there were certain deficiencies in ecological protection and environmental governance. Regarding evolutionary trends, China's GTFP showed a modest overall fluctuation from 2013 to 2019 while maintaining an increasing trend. In 2019, the national average GTFP reached a high point of 1.0487 and thus achieved an effective level. The annual average growth rate was 4.19%, indicating the country's environmental policy was maintained throughout this time.

In terms of sub-regions, the GTFPs in China's eastern, central, and western regions maintained a growth trend. The eastern regions' average GTFP value (1.0228) was highest, followed by the western region (0.8297), and the central region (0.8286), with notable differences within regions. Moreover, the average annual GTFP value in the eastern region of the country during the sample observation period exceeded the national level. The reason is that eastern cities consider ecological balance and economic growth. Meanwhile, the central region's GTFP was similar to that of the national level. For the western region, the average GTFP was the lowest, and lower than that of the national level. It is possible that the lackluster economic growth, the lack of effective exploitation, and low environmental protection awareness impeded the green economy. That is, the regional economic gap is not only reflected in the economic level but also economic quality.

4.2 Spatial correlation analysis

To avoid errors in the spatial econometric model, we assessed whether the digital economy and GTFP were spatially autocorrelated before conducting the econometric test. We also examined the spatial dependence characteristics of the different regions through the local spatial autocorrelation index using the following formulas. W presents the spatial weight matrix, which is identical to section 3.2.2. X_i and X_j represent the digital economic GTFP values of region i and region j, n is the regional sample size.

$$Global\ Moran'sI = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(X_i-\bar{X})(X_j-\bar{X})}{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(X_i-\bar{X})^2}$$

<!--Q10: Check that all equations and special characters are displayed correctly.-->

$$Local\ Moran'sI = \frac{n(X_i-\bar{X})\sum_{j=1}^{n}W_{ij}(X_j-\bar{X})}{\sum_{i=1}^{n}(X_i-\bar{X})^2}$$

4.2.1 Global spatial autocorrelation analysis

The Moran's index I) of GTFP and digital economy were both greater than 0 in Table 2, and the statistical testing indicated that GTFP and the digital economy had a substantial positive spatial autocorrelation. Overall, both digital economy and GTFP were affected by neighboring regions, showing an unstable state that resulted in unbalanced regional development.

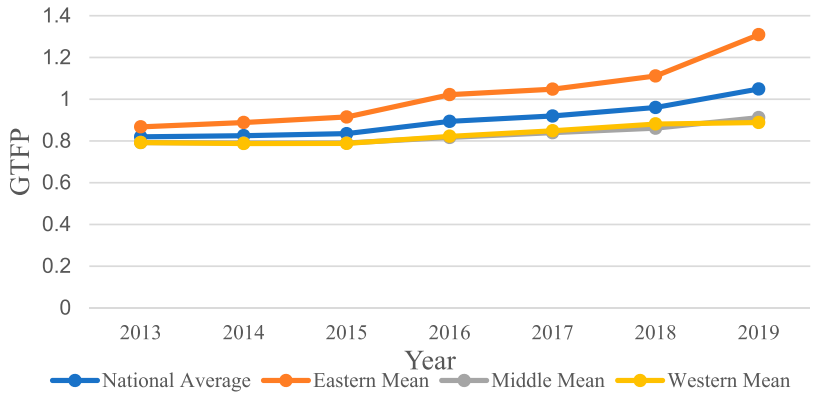

FIGURE 2
Regional green total factor productivity levels based on the super-efficient SBM model.

TABLE 2 Global Moran's I.

	INDEX		GTFP	
Year	Moran's I	*p*-value	Moran's I	*p*-value
2013	0.155	0.039	0.119	0.084
2014	0.173	0.027	0.113	0.090
2015	0.190	0.018	0.131	0.067
2016	0.160	0.035	0.219	0.011
2017	0.146	0.046	0.276	0.003
2018	0.133	0.057	0.288	0.002
2019	0.141	0.049	0.279	0.002

4.2.2 Local Moran's I

The local Moran's I evidence the spatial aggregation features of the regional provinces (Figures 3, 4). The spatial agglomeration status of GTFP and the digital economy were investigated using the local Moran's I for 2015 and 2019. Two obvious aggregation areas were evidenced: i) high-high and low-low aggregation in the first and third quadrants respectively, ii) provinces with high (low) values of the digital economy tended to cluster with provinces which with high (low) values of GTFP. This evidence demonstrates a significant positive spatial correlation. Additionally, whether it was GTFP or the digital economy, significantly more provinces appeared in the third quadrant than in the first quadrant, indicating that GTFP and digital economy development were still at a low level in most provinces in 2015–2019. There was no obvious provincial relocation in this period, indicating that some departments did not achieve significant results in the implementation of policy regulation. While actively responding to the national call, each province and city should earnestly understand their own development status, explore a reasonable and effective development path, and strive to migrate to the first quadrant.

4.3 Analysis of spatial measurement results

4.3.1 Model testing

As the spatial autocorrelation test showed that the digital economy and GTFP were significantly correlated. Therefore, a spatial econometric model was used to further test the relationship. First, a model applicability test was conducted according to the general ordinary least squares (OLS) model to determine whether the model contained a spatial lag or a spatial error term (Table 3). Lagrange Multiplier Test (LM) showed that the LM spatial error value (114.318) was significantly higher than the LM spatial lag value (78.856), and the value of the robust (R)-LM spatial error (35.677) was higher than that of the R-LM spatial lag (0.114). However, to avoid residual errors due to autocorrelation on the model results, further estimations were conducted using the spatial Durbin model. Further model degradation, likelihood ratio (LR), and Wald tests were significant, thus rejecting the null hypothesis. Overall, model testing revealed that dual-fixed SDM was the most suitable model.

4.3.2 SDM analysis

The outcomes of the dual fixed effects estimation were represented by Table 4 models 3) and 4), whereas models 1) and 2) reflected the time and spatial fixed regression, respectively. The results indicate the SDM autocorrelation coefficient rho was significantly positive, revealing that GTFP had a positive spatial spillover effect, accordant to the previous spatial correlation test results. The direct and spatial lag coefficients of the spatial

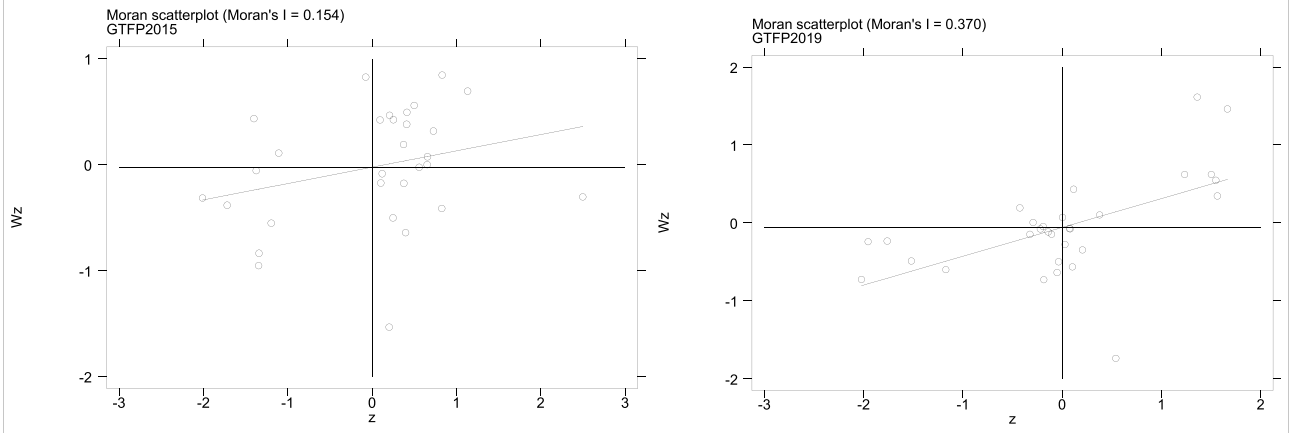

FIGURE 3
Moran's I scatter plots of green total factor productivity in 2015 and 2019 for the 30 provinces.

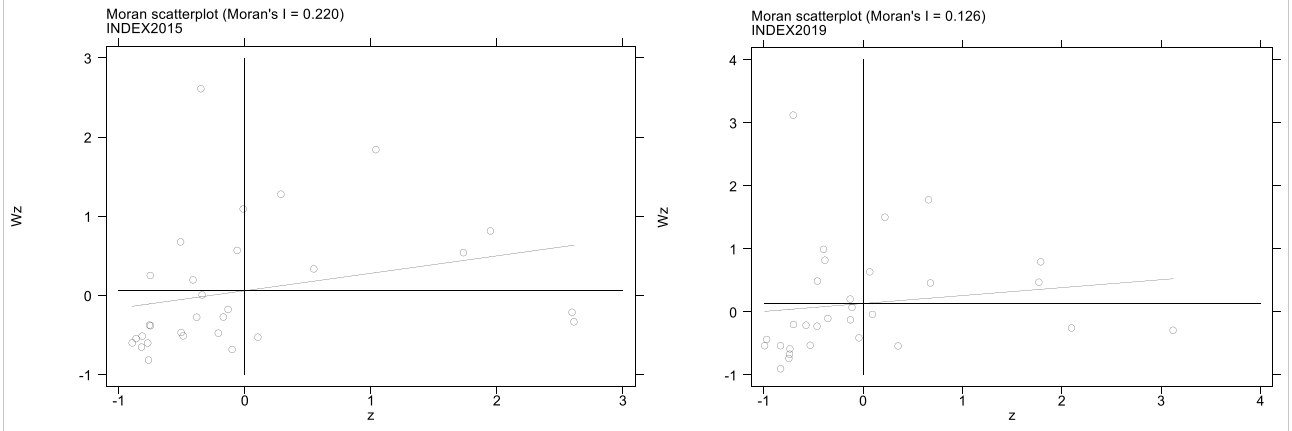

FIGURE 4
Moran's I scatter plots of index in 2015 and 2019 for the 30 provinces.

economy remained positive and significant, revealing that the improvement of digital economy on GTFP in regions and neighboring regions occurred, thus verifying Hypothesis 1.

4.3.3 Spatial effect decomposition

From a spatial perspective, the above model cannot fully reflect how the digital economy affected GTFP in a region and neighboring regions. Consequently, adopting the partial differential method to calculate the spatial distribution of the GTFP, based on LeSage and Pace (2009) This effect was decomposed (Table 5).

The digital economy's direct effect coefficient on GTFP was 0.1498, revealing that economic digital development shifted the real economy from "extensive development" to "high

TABLE 3 Model testing.

Test	Statistics	p-value
LM spatial error	114.318***	0.000
Robust LM spatial error	35.677***	0.000
LM spatial lag	78.756**	0.000
Robust LM spatial lag	0.114	0.735
LR_Spatial_lag	49.95***	0.000
LR_Spatial_error	59.58***	0.000
Wald_Spatial_lag	62.69***	0.000
Wald_Spatial_error	53.51***	0.000

TABLE 4 SDM regression results.

Variable	Time-fixed effects	Spatial-fixed effects	Dual-fixed effects	Dual-fixed effects
	1)	2)	3)	4)
INDEX	0.1072**	0.0860*	0.0853*	0.1361**
	(2.2511)	(1.6553)	(1.8625)	(2.5699)
PGDP	-1.3506***	-0.0403		-0.4720
	(-4.6581)	(-0.0711)		(-0.8575)
PGDP2	1.3975***	-0.0683		0.1590
	(5.0947)	(-0.2232)		(0.5352)
FDI	0.2707***	0.2359***		0.2272***
	(3.7363)	(3.9383)		(3.9684)
ENV	1.0615	-1.7256**		-1.4860**
	(0.7714)	(-2.2965)		(-1.9825)
FINANCE	-0.0217	-0.0103		-0.0247
	(-1.0632)	(-0.2762)		(-0.6554)
EDU	-0.2143**	0.5122***		0.4431***
	(-2.1335)	(3.1878)		(2.8064)
W*INDEX	0.0393	0.0794	0.1142*	0.2754**
	(-0.4351)	(0.7863)	(1.8659)	(2.4212)
W*PGDP	1.5778**	-1.7884**		-5.4310***
	(2.2758)	(-2.1355)		(-4.8260)
W*PGDP2	-0.6894	1.3959***		3.1958***
	(-1.1159)	(3.2091)		(5.4632)
W*FDI	-0.3301**	0.0512		-0.0053
	(-2.2788)	(0.5329)		(-0.0545)
W*ENV	5.3081**	4.5994***		6.4213***
	(2.2956)	(3.0052)		(4.1892)
W*FINANCE	0.0584	0.0322		-0.1588**
	(1.6178)	(0.5854)		(-2.1116)
W*EDU	0.7681***	0.4037		0.1910
	(3.5982)	(1.4333)		(0.6395)
Spatial rho	0.3354***	0.3421***	0.4743***	0.1666*
	(3.7652)	(4.2050)	(6.7526)	(1.7991)
Constant	0.0299***	0.0044***	0.0059***	0.0040***
	(10.1129)	(10.1251)	(10.0322)	(10.2123)
N	210	210	210	210
R-sq	0.469	0.056	0.232	0.109

TABLE 5 Spatial effect decomposition.

Variable	Direct effects	Indirect effects
INDEX	0.1498***	0.3438***
	(2.7281)	(2.8070)
PGDP	-0.7132	-6.2828***
	(-1.3447)	(-5.4897)
PGDP2	0.3070	3.6726***
	(1.1038)	(6.1265)
FDI	0.2284***	0.0348
	(4.1469)	(0.3161)
ENV	-1.2183*	7.2520***
	(-1.6818)	(3.8431)
FINANCE	-0.0300	-0.1889**
	(-0.8029)	(-2.2087)
EDU	0.4554***	0.2966
	(2.7986)	(0.8858)

development." The green transformation of quality development indicates the advancement of enterprises' operation mode. Moreover, it indicates the traditional industry is gradually shifting towards a high-output, low-pollution mode, which reduces environmental pollution, and promotes GTFP. Perspective on the spillover effect, coefficient value was 0.3438 (Table 5) which is more significant that of the promotion effect on adjacent regions. Which evidences that the digital economy has produced the demonstration effect for neighboring regions, prompting imitation to improve production efficiency, accelerate technology transfer and factor spillovers, and promote the development of GTFP.

Regarding control variables, the PGDP spillover influence was negatively significant, demonstrating that over-exploitation and pursuit of economic growth, and will result in ecological degradation and consequently raise the environmental burden, hindering green development. Meanwhile, the economic development squared coefficient (PGDP2) was positive and had a U-shaped relationship (You and Lv, 2018; Mughal et al., 2022; Sun, 2022), indicating that China's economic development accords with the EKC hypothesis. The FINANCE indirect effect was negative, hindering the GTFP. This can be attributed to the unreasonable allocation of financial resources, with capital elements flowing to other industries, resulting in limited funds and obstructing the region's green economy. However, the direct effect is negligible had no impact on adjacent regions. Environmental regulation's (ENV) indirect effects on GTFP revealed a significant promotion effect, displaying that China's recent investment in environmental protection and regulation has yielded significant results, while environmental regulation in the region also generates competition and

TABLE 6 Robustness test results.

Variable	1)	2)	3)	4)
INDEX	0.8019***	0.7064***	0.1337**	0.1202**
	(3.16)	(2.65)	(2.52)	(2.19)
W*INDEX			0.2788**	0.3036**
			(2.45)	(2.35)
Spatial rho			0.1620*	0.1641*
			(1.73)	(1.72)
Control	NO	YES	YES	YES
Year	YES	YES	YES	YES
City	YES	YES	YES	YES
Kleibergen-Paap rk LM statistic	11.11	5.265		
	[0.000]	[0.002]		
Kleibergen-Paap rk Wald F statistic	17.2	17.93		
	[16.38]	[16.38]		
N	210	210	210	210
R-sq	0.037	0.392	0.107	0.059

TABLE 7 Spatial Durbin model regression for technological innovation.

Variable	1)	2)
INDEX	0.0712	0.1454**
	(1.2386)	(2.4819)
TECH	-0.2417***	-0.2006***
	(-4.1681)	(-3.6786)
INDEX*TECH	0.0702***	0.0458***
	(3.8584)	(2.6129)
W*INDEX	0.1921**	0.3885***
	(2.0678)	(3.1106)
W*TECH	0.2771***	0.2580***
	(3.0957)	(2.6426)
W*INDEX*TECH	-0.0900***	-0.0917***
	(-3.0134)	(-2.8052)
Spatial rho	0.5132***	0.1650*
	(7.4584)	(1.7588)
_Cons	0.0052***	0.0036***
	(9.9491)	(10.2140)
City	No	Yes
Year	No	Yes
Control	No	Yes
N	210	210
R-sq	0.145	0.013

TABLE 8 Spatial effect decomposition of technological innovation.

Variable	Direct effects	Indirect effects
INDEX	0.1644***	0.4911***
	(2.7592)	(3.3470)
TECH	-0.1926***	0.2780**
	(-3.6111)	(2.5603)
INDEX*TECH	0.0429***	-0.1030***
	(2.5899)	(-2.8044)

imitation effects, propelling the green development of neighboring regions. Nevertheless, a significant negative direct effect was observed, likely due to excessive environmental regulation causing a waste of labor and material resources, which is counterproductive as it can generate a "cost of compliance" effect and hinder GTFP. The FDI had a favorable direct impact on GTFP, implying that foreign investment significantly contributed to the GDP growth of China. Moreover, foreign investment introduces advanced environmental protection technology and management experience, which drives green transformation in enterprises and improves environmental quality. Human capital (EDU) had a beneficial impact on GTFP, and higher education level is equivalent to an increase in composite talents, which promotes the transformation of green achievements and provides talent assistance for the long-term growth of the green economy.

4.3.4 Robustness test

In this study, the model's robustness was examined using endogenous discussion, Winsorize, and by adding control variables.

1) Instrumental variables approach. Referring to Nunn and Qian (2014), and Zhao T. et al. (2020), we introduced a panel instrumental variable with a time-varying variable. Specifically, the interaction was constructed between the number of landlines in 1984 and the amount of Internet users nationwide in the previous year to indicate the instrument variables of the digital economy of that year. Table 6 model 1) and 2) show that the Kleibergen Paap rk LM statistic was significant, while the Kleibergen Paap rk Wald F statistic was greater than the critical value at the 10% level of Stock Yogo. This demonstrates that the instrumental variable was reasonable and effective. Nevertheless, the digital economy's coefficient was also significant.
2) Winsorize. Considering the potential effects of outliers, in this study a 1% bilateral tail reduction on the explained variables was conducted. The result is displayed in model 3). The digital economy coefficient remained positively significant, which is, consistent with the findings in this study.
3) Increase control variables. To avoid the potential effects of differences in economic development characteristics of different regions on the empirical results, control variables were increased, namely, government intervention (fiscal expenditure as a proportion of GDP), marketization level (Zhou and Li, 2021), and population density (total population at the end of the year). Model 4) in Table 6 reveals that the digital economy continued to be favorably significant on GTFP, so the model conclusion is reliable.

4.3.5 Analysis of moderating effects

Results of the SDM regression with technological innovation as adjustment variables (models 1) and 2) in Table 7) showed a significantly positive interaction between technological innovation and the digital economy which exerted a considerable influence on regional GTFP. This verified Hypothesis 2. Meanwhile, a significantly negative indirect effect was observed, showing that technological innovation

can impede a positive connection between the digital economy and GTFP, and thereby verified Hypothesis 3. In addition, the spatial autocorrelation coefficients of models 1) and 2) were significantly positive, further supporting that GTFP had a spatial spillover effect.

The spatial effects were decomposed and analyzed to further explore the moderating impacts of technological innovation (Table 8). Overall, the addition of the variables resulted in significant effects on digital economy, consistent with our conclusions in previous sections. The interaction between technological innovation and the digital economy provided a substantial effect on GTFP with direct effect coefficients on the GTFP of 0.0429. Thus, technological innovation significantly improved the local economies. This implies that a higher level of technological innovation can support green technology advancement more effectively, leading to better improved environmental pollution control and digital technology innovation, actively achieving technological change and green transformation, and driving the growth of regional GTFP. Nevertheless, a significant negative spillover effect was observed. According to the "pollution sanctuary" hypothesis, local environmental regulations drive high-polluting industries to relocate to nearby areas, aggravating environmental pollution there. Which lessens the benefits of convergence, rendering innovation ineffective and impeding the growth of GTFP in neighboring regions.

5 Conclusions and recommendations

Based on panel data from 2013 to 2019, digital economy and GTFP were measured. The spatial econometric model was used to analyze how the digital economy affects GTFP. The following conclusions were drawn:

1) During the 2013–2019 observation period, China's GTFP maintained a continuous growth trend, indicating that ecological protection policies have recently been implemented. Significant regional differences in GTFP were observed. The eastern region demonstrated the highest GTFP with 1.0228, while the central region revealed the smallest with 0.8286.
2) The spatial autocorrelation test showed that the country's GTFP was significantly spatially autocorrelated, manifesting spatial agglomeration. The local autocorrelation test evidenced the GTFP's spatial heterogeneity in different provinces, with provinces of high (or low) GTFP agglomerating with each other. Further, the SDM showed a positive spatial coefficient, indicating that China's GTFP had both spatial dependence and a positive spatial spillover effect. The decomposition of spatial effects showed that the digital economy promoted GTFP in each province driving the growth of GTFP in neighboring provinces relying upon the spatial spillover effect; moreover, its indirect effect (0.3438) was greater than its direct effect (0.1498).
3) In terms of adjustment variables, the region's technological innovation positively promoted the relation between the GTFP and the digital economy, negatively regulating the surrounding region digital economy's impact on GTFP. According to the findings, this article proposed the following three policy recommendations:

1) Vigorously develop the digital economy to support green development. Actively guide the integration of traditional industries with the digital economy to enhance economic efficiency and develop industrial elements through the flow of data and information. On the one hand, importance should be attached to the digital information industry by promoting digital industrialization, 5G, and artificial intelligence within existing networks. While vigorously developing the internet platform economy and improving cross-platform cooperation in the digital economy industry for generating new industries and new business models. On the other hand, within the traditional economy, the integration of AI should be encouraged and low pollution and high output should be strived for.
2) Strengthen environmental regulations and reduce environmental pollution. As the research evidenced that government intervention significantly promoted GTFP. Consequently, the government should adjust and formulate reasonable environmental regulation policies and increase the investment in energy saving, zero pollution, and other clean energy and green innovation technologies. Simultaneously, regional environmental regulation should be incorporated into the official performance appraisal system, and the supervision and punishment for environmental violations should be strengthened. Enterprises should also strictly abide by national pollution discharge indicators, implement energy conservation, apply new industrial development patterns, and improve the previous resource-dependent model and the efficiency of pollution control devices.
3) Optimize the industrial structure and accelerate green transformation. Steadily advancing the development of primary and secondary industries, while centering around the growth of high-tech industries. Moreover, the opportunities from digital globalization should be pursued. Traditional industries should be conducted through the penetration and diffusion of information technology. Improving and enhancing the quality and efficiency of products in the entire industry, reducing unnecessary waste of resources, and enhancing the green transformation of the industrial structure through information resource sharing are equally important.
4) Strengthen regional linkages and improve GTFP. As GTFP has an obvious spatial spillover effect, it is imperative to break down regional barriers, strengthen exchanges and cooperation between regions, promote an exchange of green technology and information elements between regions, and form a regional linkage of resource exchange. This will promote green technology and knowledge spillover,

comprehensively improve GTFP, and achieve common progress.

Limitations of this paper: 1) The sample data was only from a 7 years period, and detailed information was difficult to obtain due to a lack of data availability. 2) This study lacked did not investigate whether the digital economy and GTFP have a non-linear relationship (Pan et al., 2022), moreover, there may be other potential mediating channels for the mechanism of the digital economy on GTFP, such as energy structure, industrial transformation that were not revealed here. The aforementioned points represent the current study's limitations and should be taken into account going forward.

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

Writing-original draft, methodology, resources, writing-review and editing XS; conceptualization, data curation KJ; formal analysis, investigation, funding acquisition XZ; project administration, software ZC; supervision, validation, visualization JX.

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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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Digital finance, environmental regulation, and green development efficiency of China

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In the context of the increasingly prominent contradiction between economic development and ecological environment, how to promote green development has become the core of sustainable economic development. Digital finance is an innovative financial model with a high degree of integration of finance and digital technology and provides a new opportunity for achieving green development. Based on identifying the mechanisms of digital finance and environmental regulation on green development efficiency, this research uses the directional distance function and Malmquist-Luenberger index to measure the green development efficiency of 30 provinces in China from 2011 to 2020 and then employs a dynamic panel GMM model to empirically analyze the relationships among digital finance, environmental regulation, and green development efficiency. The results of the study show the following. 1) Digital finance contributes to the efficiency improvement of green development. 2) Environmental regulation has not yet crossed the Porter's inflection point and still has a dampening effect on green development efficiency. 3) The synergy between digital finance and environmental regulation has a positive impact on green development. 4) Digital finance alleviates the financing constraints arising from environmental regulation and to some extent weakens the negative effect of environmental regulation on the efficiency of green development. In view of this, the government should give full play to the active role of digital finance in eco-environmental governance, optimize the top-level design of environmental regulation, and promote industrial structure upgrading and optimal allocation of financial resources.

KEYWORDS

digital finance, environmental regulation, green development efficiency, dynamic panel GMM model, Economic Transformation

1 Introduction

It has been more than 10 years since the United Nations proposed the concept of inclusive finance in 2005, and the global practice of inclusive finance has completed the development process of "microfinance—Internet finance—digital inclusive finance". It has made an important contribution to global financial equity and sustainable development. Digital inclusive finance has become a new idea of inclusive financial development and an innovative hot spot in the financial field, which meets the requirements of the digital intelligent era. Currently, the digital wave has largely affected various fields of the traditional economy. In addition, coupled with the sudden outbreak of the new crown pneumonia epidemic, the financial industry has accelerated its transformation to digitalization. Therefore, digital inclusive finance is considered as an important driver for the green transformation of the economy (Ding et al., 2022). The 20th Party Congress report

pointed out that promoting green and low-carbon economic and social development is a key link to achieve high-quality development, and achieving green development will certainly put forward higher requirements for ecological and environmental governance. The Global Environmental Performance Index (EPI) report jointly released by Yale University and other research institutions in 2020 showed that China ranks 120th with 37.3 points, and environmental problems are still very serious. In order to reverse the deterioration of the ecological environment and alleviate the outstanding contradiction between the ecological environment and economic development, President Xi Jinping announced at the Climate Ambition Summit on 12 Dec 2020 his solemn commitment to "strive to peak CO_2 emissions by 2030 and strive to achieve carbon neutrality by 2060", which also means that the intensity of China's environmental regulations will be further increased (Shi F. et al., 2022). Under the constraints of intensifying environmental pollution and weak transformation of the green economy, how to promote green development has become the core importance of sustainable economic development. Environmental regulation is considered to be an important means to promote the harmonious development of economy and ecology. It encourages enterprises to change their original production methods, strengthen technological innovation, and improve the efficiency of resource factor utilization and environmental efficiency, which requires sufficient funds to ensure technological innovation (Chen et al., 2022a; Chen et al., 2022b; Chen et al., 2022c). As the bloodline of the national economy, finance is an important tool for optimizing resource allocation and macro-control (Zhao and He, 2022). With the widespread application of modern digital technology in the financial sector, the new industry of digital finance has emerged from traditional finance with the empowerment of digital technology and is showing rapid development.

According to the Digital Finance Index Report released by Peking University in 2021, China's digital inclusive finance has shown a rapid development trend in the past decade with an average annual growth of 29.1% in the Digital Finance Index. Thanks to its advantages of inclusiveness, convenience, and efficiency, digital finance has begun to reshape the pattern of economic development by expanding financing channels and optimizing resource allocation. It has gradually become a new driving force leading scientific and technological innovation, driving economic and social transformation and development, and providing a new opportunity for the improvement of green development efficiency. Green development is a concept with rich connotation. It not only considers energy saving and emission reduction, technological innovation, industrial transformation and other changes in economic growth drivers, but also involves the effect of economic growth. It pursues sustainable growth of environment, resources and economy (Shi Y. et al., 2022; Wang et al., 2023; Zou et al., 2023). In the current macro-level context of tightening environmental regulations, how does digital finance affect green development? What about the synergistic impact of digital finance and environmental regulation on green development efficiency? What is the intrinsic mechanism of interaction between the three? An in-depth exploration of the above topics has important practical value and theoretical significance for exploring the eco-economic and social benefits of digital finance.

Scholars around the world have presented a lot of research results concerning the impact of digital finance and environmental regulation on ecological economy and society, but in the new development pattern, scholars are still at the preliminary stage of exploring the impact mechanism and causal relationship between them. In order to clarify the literature related to digital finance, environmental regulation, and green development, this paper will sort out the existing papers from the following aspects.

First, from the perspective that digital finance affects green development efficiency, some scholars stated that digital finance improves the financing environment, enhances corporate green technology innovation, and supports green development. Technological innovation of enterprises can improve production efficiency and reduce environmental pollution, but enterprises need long-term and stable capital investment to carry out green innovation activities (Yu et al., 2021). However, many enterprises' technological innovation activities are constrained by financing (He et al., 2022), and traditional financial institutions are unable to provide them with sufficient financial support (Bo, 2021). Other scholars considered that digital finance has greatly reduced the threshold and cost of financial services by using digital technologies such as the Internet, big data, and cloud computing to provide financial services to enterprises (Ozili, 2018) and expanding the coverage of financial services (Liu et al., 2021). In addition, digital finance can promote the upgrading of industrial structure by regulating the economy and optimizing resource allocation (Shofawati, 2018), thus enhancing the level of green development (Ding et al., 2022). Some other scholars found that digital finance can facilitate the innovation of financial instruments, such as green funds and green bonds (Antimiani et al., 2017; Cui and Huang, 2018), to promote green development. Digital finance improves the efficiency of green development by creating new financial markets that reduce the risks faced by enterprises and the social environment (Turski, 2018). Digital finance, driven by information technologies such as big data, block chain, and cloud computing, breaks through time and space limitations, enables resource sharing and interoperability, and facilitates economic green transformation and green development with the advantages of low cost, high efficiency, and wide coverage (Sun, 2020).

Second, from the perspective of the impact of environmental regulation on green development, the impact mechanism is complex, and there is no unified conclusion on the relationship between the two in the academic community. The first view sees a positive role for environmental regulation in promoting green development. Environmental regulation promotes advanced industrial structure and low carbon energy consumption through the technological innovation effect, innovation compensation effect, and investment screening effect (Huang and Lei, 2021; Behera and Sethi, 2022; Fan et al., 2022), while attracting high-end green production technology of good quality to realize green the spillover effect, thus promoting green development. Technological innovation has been shown to be effective in mitigating environmental degradation (Chien et al., 2021). The second view is that environmental regulations have a negative impact on the efficiency of the green economy, that stronger environmental regulations lead to higher environmental protection and governance costs, which affect output efficiency and economic development (Cai and Ye, 2020; Li and Ma, 2022), and that stronger environmental regulations lead to the allocation of financial resources to the secondary sector, thus inhibiting the improvement of green development efficiency. The third view argues that the impact of environmental regulation on the efficiency of the green economy is stage-specific and non-linear (Zhao and He, 2022). Porter and van der Linde (1995) proposed the

Porter hypothesis, which states that moderate environmental regulation can stimulate firms to innovate in R&D and improve their output efficiency through technological innovation to compensate for the increased compliance costs of environmental regulation (Porter and van der Linde, 1995). As the topic progressed, scholars further subdivided the study in terms of industries, regions, and environmental regulatory tools (Yin et al., 2022) and explored the differences in the impact of various environmental regulatory tools and types of industries and regions on green technology innovation (Feng et al., 2022).

In summary, scholars have presented rich findings on digital finance, environmental regulation, and green development, but few of them have included the interactions among digital finance, environmental regulation, and green development into a unified analytical framework, have not yet responded positively to the synergistic impact and intrinsic correlation between digital finance and environmental regulation on the efficiency of green development, and have not reached a unanimous conclusion on the environmental and economic effects of digital finance. Compared with existing studies, this paper tries to contribute in the following three aspects: 1) to identify theoretically the mechanism of digital finance, environmental regulation, and their synergistic effects on green development, enriching the literature on digital finance and environmental regulation; 2) to explore mainly how the synergistic effects of digital finance and environmental regulation affect regional green development in the context of the current situation of tightening environmental regulation by local governments and to enrich relevant literature on understanding the relationship between them. Specifically, the directional distance function and Malmquist-Luenberger productivity index are used to measure green development efficiency in China, and the composite index method is used to construct a comprehensive index of environmental regulation intensity, and a dynamic panel GMM model is applied to empirically analyze the effects of digital finance and environmental regulation on green development efficiency.; and 3) to examine the heterogeneous effects of the three dimensions of digital finance on promoting green development. The above research provides a basis for government departments to formulate environmental regulatory policies that are appropriate to the level of development of digital inclusive finance.

The research arrangement of this paper is as follows: Section 2 is the Theoretical Mechanism and Research Hypotheses, Section 3 is Methodology, Section 4 is the empirical analysis, and Section 5 is the conclusions and policy recommendations.

2 Theoretical mechanism and research hypotheses

2.1 The impact of digital finance on green development efficiency

Digital finance has strong green attributes and plays an important role in the process of promoting green development. Different from traditional finance, digital finance has the advantages of low cost, universality, and high efficiency with the empowerment of digital technology such as big data and artificial intelligence, providing a new engine to promote green development and improve economic quality. Specifically, digital finance has an impact on green development in the following ways. First, it promotes the upgrading of industrial structure to promote green development (Pai, 2016). On the one hand, modern digital technology can be used to accurately identify green innovation projects, guide the flow of funds to low-carbon green and high-tech industries, and promote the optimization and upgrading of industrial structure. On the other hand, it can stimulate green consumption demand through differentiated financial products and services, further force the transformation and upgrading of enterprises, accelerate the layout of green industry chain, and thus promote green development.

Second, digital finance helps improve the efficiency of optimal resource allocation and promote green development efficiency. Digital finance has broken the "two-eight law" of the traditional financial system, reshaped the financial system to a certain extent, improved the accessibility of financial resources, enabled financial services to reach the long tail of small- and micro-size enterprises and other groups discriminated against by capital (Gomber et al., 2018; Li et al., 2020), optimized the distribution system, and thus enhanced the efficiency of green development. At the same time, the digital platform is used to continuously innovate financial products and services, broaden the boundary of financial services, establish a bridge of interconnection between the two sides of financial services, break through time and space restrictions, accurately match the demand side of the industry chain, improve financing efficiency, reduce costs, effectively alleviate the problem of resource mismatch (Kshetri, 2016; Dendramis et al., 2018), and provide strong financial support for the overall enhancement of green development.

Finally, digital finance promotes technological innovation and improves green development efficiency. Innovation is the endogenous driving force of green development. Digital finance makes up for the shortcomings of traditional finance through modern technologies such as big data and artificial intelligence (Cao et al., 2021) and provides financing services for some clean energy development, environmental protection, and other technology enterprises with its highly informative and inclusive features, reducing the R&D costs of small- and medium-size enterprises (SMEs). The promotion and application of new technologies by enterprises can reduce environmental pollution at the source and alleviate damage to the ecological environment caused by their production activities, while also opening up new ways to develop green production factors. Therefore, we propose Hypothesis 1.

Hypothesis 1. Digital finance has a facilitating effect on the improvement of green development efficiency.

2.2 The impact of environmental regulation on green development efficiency

Green development is oriented to resource conservation and environmental protection and takes environmental benefits into account on the basis of measuring economic growth. It enhances green development efficiency by reducing pollution emissions and energy inputs, and environmental regulation is an important policy tool to achieve green development (Chen et al., 2022c; Zou et al., 2022). The impact of environmental regulation on the efficiency of green development can be explained in the following ways. First, environmental regulation impacts its efficiency through the effect of technological improvement. The Porter hypothesis suggests that strengthening environmental regulations will bring about an

increase in compliance costs, but in the long run, environmental regulations force enterprises to innovate in technology, to improve their production processes and technologies, to enhance the optimal allocation of resources, to reduce pollution emissions, and to enhance green development (Ye et al., 2021; Yang, 2022).

Second, environmental regulations affect the efficiency of green development through the capital screening effect. When environmental regulations are gradually strengthened, financial institutions will gradually tend to support green enterprises or projects in the supply of funds and reduce investments in high pollution and high energy consumption enterprises or projects. This forms a fund screening effect to gradually optimize the industrial layout and promote green development efficiency (Guo et al., 2018; Song et al., 2022).

Third, environmental regulation affects green development through the input appropriation effect. The increased intensity of environmental regulations forces the government and enterprises to invest more resources in environmental protection to reduce pollution emissions, which in turn crowd out productive and profitable investments of enterprises, forming the encroachment effect of environmental protection inputs. This inevitably weakens enterprises' green innovation and R&D efforts, reduces resource allocation efficiency, and affects the improvement of green development efficiency (Song et al., 2019). However, studies have found that the improvement of green development efficiency is mainly caused by technological progress (Chen et al., 2020), and the negative effects of environmental regulation can be fully compensated by the technological improvement effect (Ouyang et al., 2020). Therefore, we propose Hypothesis 2.

Hypothesis 2. Environmental regulation has a facilitating effect on the improvement of green development efficiency.

2.3 Digital finance, environmental regulation, and green development efficiency

The key to achieving green development is to improve environmental policies and systems. Local governments should not only promote green technological innovation through environmental regulation means and force the green transformation and upgrading of high pollution and high energy consumption industries, but also promote financial innovation, guide the green development of the local economy through green credit and green finance, and support green technological innovation and application (Zhang et al., 2022). The implementation of environmental regulations has placed higher demands on production activities. In order to meet environmental regulations, companies have to increase investment into research and development (R&D) of environmental protection and pollution control technologies and improve production processes and efficiency. While endogenous financing can alleviate some of the financial pressure, the need for a continuous supply of funds for technological innovation R&D and the uncertainty of short-term output make it particularly important for companies to seek more external sources of financing.

The development of digital finance provides financial support for environmental regulation to better promote green development and technological innovation. Relying on modern digital technologies such as the Internet, big data, and cloud computing, digital finance brings together idle funds in society through digital platforms, and under the joint action of the "visible hand" of the government and the "invisible hand" of the market it promotes the flow of financial resources to more long-tail groups, breaks the restriction of exogenous financing, and provides financial support for technological innovation and green development. At the same time, environmental regulation can significantly improve environmental information disclosure, provide information screening for financial institutions, and promote green credit placement. Therefore, digital finance can alleviate the financing constraints arising from environmental regulations and weaken the negative impact of environmental regulations on green development efficiency to a certain extent, while environmental regulations promote the development of digital finance to a certain extent and guide financial institutions to explore the environmental blue ocean market. In summary, we propose Hypothesis 3.

Hypothesis 3. The interactive effect of digital finance and environmental regulation has a catalytic effect on the improvement of green development efficiency.

The influence mechanism of digital finance, environmental regulation and green development efficiency is shown in Figure 1.

3 Methodology

3.1 Model setting

In order to test the intrinsic connections among digital finance, environmental regulation, and green development efficiency and to better analyze the impact of the synergy between digital finance and environmental regulation on green development efficiency, this paper adds the interaction term of digital finance and environmental regulation to the model and centralizes this. The econometric model is set in the following form.

$$GTFP_{it} = \alpha_0 + \rho_1 GTFP_{i,t-1} + \rho_2 GTFP_{i,t-2} + \beta_1 lndf_{it} + \beta_2 er_{it} + \beta_3 lndf_{it} \times er_{it} + \sum_{i=1}^{4} \omega_i control_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

In Eq. 1, $GTFP$ is green development efficiency, df is digital finance development index, er is environmental regulation, $control$ is control variables, $lndf_{it} \times er_{it}$ is the interaction term between digital finance and environmental regulation (interaction term centralized treatment), i is provincial cross-sectional unit, t is year, μ is individual fixed effect, ε is random disturbance term, and $\alpha, \beta,$ and ω are parameters to be estimated. $GTFP_{i,t-1}$ and $GTFP_{i,t-2}$ are the green development efficiency at lag one and lag two, respectively, and are put into the model as explanatory variables. However, this creates endogeneity problems among the model variables and also leads to autocorrelation in the model.

To solve the above problem, we use the GMM method for estimation, and the endogeneity problem can be effectively solved by introducing the lagged terms of the explanatory variables as instrumental variables. First, the individual effects of the model are eliminated by doing a first-order difference for Eq. 1.

$$\Delta GTFP_{it} = \rho_1 \Delta GTFP_{i,t-1} + \rho_2 \Delta GTFP_{i,t-2} + \beta_1 \Delta lndf_{it} + \beta_2 \Delta er_{it} + \beta_3 \Delta lndf_{it} \times er_{it} + \sum_{i=1}^{4} \omega_i \Delta control_{it} + \Delta \varepsilon_{it} \quad (2)$$

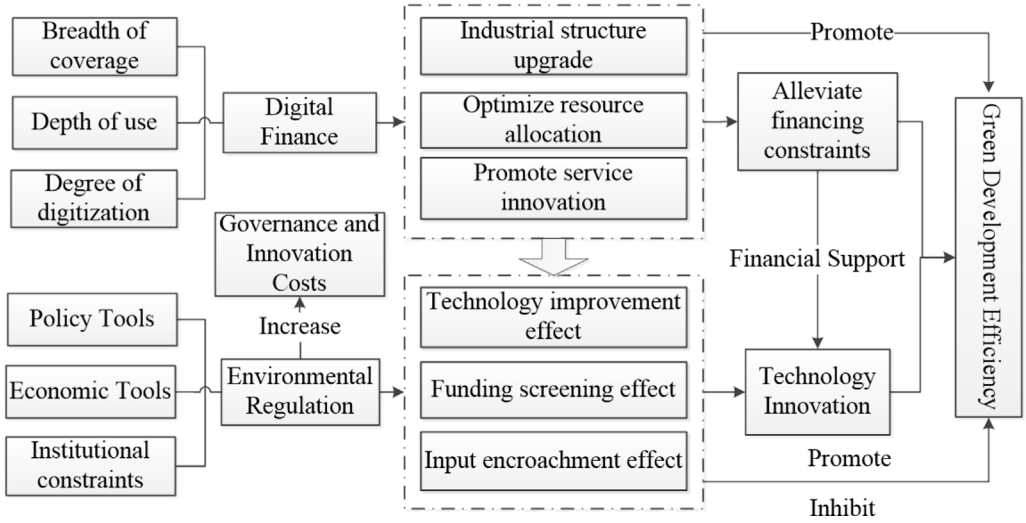

FIGURE 1
Influence mechanism of digital finance, environmental regulation and green development efficiency.

The lag term still correlates with $\Delta\varepsilon_{it}$, the endogeneity problem of model (2) still exists, and so further instrumental variables can be sought to obtain consistent estimates. Arellano and Bond (1991); Blundell and Bond (1998) propose two types of methods, differential GMM and systematic GMM, for regressing dynamic panel models, which can effectively solve the endogeneity problem (Arellano and Bond, 1991; Blundell and Bond, 1998). However, the premise of using this method is that the perturbation terms are not autocorrelated. Therefore, we choose the differential GMM model for testing.

3.2 Green development efficiency measurement

Green development is a new model to achieve sustainable development by protecting the ecological environment under the constraints of ecological and environmental capacity and resource carrying capacity. Green development requires economic growth while reducing the impact on the ecological environment, emphasizing the mutual unity and coordinated development of the two (Zhao and He, 2022; Chen et al., 2022b). The existing methods on measuring green development efficiency mainly include Data Envelopment Analysis (DEA), Stochastic Frontier Analysis (SFA), Total Factor Productivity (TFP), and other efficiency measurement methods. In this paper we use the directional distance function by considering the undesirable output and the Malmquist-Luenberger productivity index to measure green development efficiency (Chen et al., 2022a). This method, proposed by (Chung et al., 1997), applies the directional distance function containing non-desired outputs to the Malmquist model to obtain the Malmquist-Luenberger index (ML index for short). The directional distance function is defined as follows:

$$\overrightarrow{D_0}\left(x, y, b; g_y, -g_b\right) = sup\left\{\beta: \left(y + \beta g_y, b - \beta g_b\right) \in p(x)\right\} \quad (3)$$

In Eq. 3, $\overrightarrow{D_0}$ is the distance function, x, y, and b are the input vector, desired output vector and non-desired output vector, respectively, g is the direction vector, $g = (g_y, -g_b)$, and β is the distance function value.

$$\overrightarrow{D_0^t}\left(x_k^t, y_k^t, b_k^t; y_k^t, -b_k^t\right) = max\,\beta \quad (4)$$

$$s.t.\begin{cases} \sum_{k=1}^{k} z_k^t y_{km}^t \geq (1+\beta) y_{km}^t, \ m = 1, 2 \ldots, M \\ \sum_{k=1}^{k} z_k^t b_{ki}^t = (1-\beta) b_{ki}^t, \ i = 1, 2 \ldots, I \\ \sum_{k=1}^{k} z_k^t x_{kn}^t \leq x_{kn}^t, \ n = 1, 2 \ldots, N \\ z_k^t \geq 0, \ k = 1, \ldots, K \end{cases} \quad (5)$$

In Eq. 5, z_k^t is the k^{th} observation weight, M, I, and N are desired output, non-desired output, and types of input factors, respectively, t is the period, and so the ML index from period t to period $t+1$ can be expressed as follows:

$$ML\_TFP_t^{t+1} = \left[\frac{\left(1+\overrightarrow{D_0^t}\left(x^t, y^t, b^t; y^t, -b^t\right)\right)}{\left(1+\overrightarrow{D_0^t}\left(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)\right)} \times \frac{\left(1+\overrightarrow{D_0^{t+1}}\left(x^t, y^t, b^t; y^t, -b^t\right)\right)}{\left(1+\overrightarrow{D_0^{t+1}}\left(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)\right)}\right] \quad (6)$$

In Eq. 6, $ML\_TFP_t^{t+1}$ greater than 0 indicates productivity growth and efficiency improvement; $ML\_TFP_t^{t+1}$ less than 0 indicates productivity decline. The measurement of ML productivity index requires comprehensive consideration of environmental, energy, resource, and other constraints. Therefore, we include the above elements in setting the input and output indicators, and the indicator selection and interpretation are explained as follows.

TABLE 1 Descriptive statistics of variables.

Variable type	Variable	Mean	Standard error	Min	Max
Explained variables	*GTFP*	0.815	0.116	0.485	1.123
Core explanatory variables	*er*	0.896	0.100	0.433	1.000
	df	217.246	96.968	18.330	431.930
	cov	198.010	96.334	1.960	397.000
	deep	212.036	98.106	6.760	488.680
	cov	290.238	117.644	7.580	462.230
Control variables	*gdp*	5.370	2.696	1.591	16.493
	indus	0.410	0.081	0.158	0.620
	innov	58602.22	8936.55	502	709725
	green	0.396	0.035	0.279	0.491
	open	0.254	0.272	0.007	1.359

1) Input indicators. Labor force, capital stock, and energy input are used as input indicators for green development efficiency, where labor force input is measured by the total number of employed persons at the end of the year. Capital stock is calculated by referring to the measurement method of Shan Haojie (Shan, 2008), using the perpetual inventory method, and the annual capital stock of each province is calculated by using 2010 as the base period with a depreciation rate of 10.96%. The amount of energy input is expressed in terms of comprehensive energy consumption—that is, the eight kinds of energy consumed by each province each year—which is converted into a uniform unit according to GB2589-2008T General Rules for Calculating Comprehensive Energy Consumption to sum up the total energy consumption of each province. The energy consumption is converted into million tons standard coal.
2) Output indicators. Output includes desired output and non-desired output, where desired output is expressed as the real GDP *per capita* of each province calculated in 2010 at constant prices; non-desired output is measured by the total annual carbon emissions and industrial triple waste emissions (i.e., three major pollution emission indicators of wastewater, waste gas and solid waste) of each province, where carbon emissions are calculated according to the formula of energy in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The formula for calculating carbon dioxide emissions provided as below.

$$E(CO_2) = \sum_{i=1}^{8} E(C) = \frac{\sum_{i=1}^{8} Q_i \times NCV_i \times CEF_i \times COF_i \times 44}{12} \quad (7)$$

In Eq. 7, $E(CO_2)$ is the total carbon emissions of eight energy consumptions, $E(C)$ is the carbon emission of energy i, Q_i is fuel consumption, NCV_i is the net heat of energy fuel i, CEF_i is the carbon emission factor of energy fuel i, COF_i is the carbon oxidation factor of energy fuel i, 44 indicates the molecular weight approximation of CO_2, and 12 represents the approximate atomic weight of carbon.

3.3 Selection of indicators

3.3.1 Explained variables

The explanatory variable in this paper is *GTFP* as measured by MaxDEA software; i.e., green development efficiency expressed as the Malmquist-Luenberger productivity index.

3.3.2 Core explanatory variables

Digital Finance (*df*). We choose the Peking University Digital Inclusive Finance Index, jointly compiled by the Digital Finance Research Center of Peking University and Ant Financial Services, to measure the level of digital finance development. The index constructs an evaluation system of digital inclusive finance in three dimensions: breadth of coverage (*cov*), depth of use (*deep*), and degree of digitization (*dig*) (Guo et al., 2020), which can comprehensively reflect the level of digital finance development in each province.

Environmental regulation (*er*). Due to the diverse characteristics of environmental regulation tools and government intervention patterns, the measures of environmental regulation by domestic and foreign scholars also differ significantly. We summarize two types of approaches. One type is measured by using a single index, including the number of inspections on the number of times enterprises discharge (Brunnermeier and Cohen, 2003), the share of pollution control investment in industrial value added, or the share of pollution control investment in GDP (Berman and Bui, 2001). Another type is to measure the intensity of environmental regulation using a composite index, which combines the aspects of managing wastewater, solid waste, and exhaust gas (Wang et al., 2022), using the entropy value method. We choose the second method to measure the intensity of environmental regulation by replacing the single index method with the comprehensive index method, consider the three wastes treatment, select the investment amount completed in wastewater treatment, investment amount completed in waste gas treatment, and investment amount completed in solid waste treatment as a proportion of industrial GDP, and use the entropy method to calculate the comprehensive

TABLE 2 Regression results of the dynamic panel GMM model.

Variables	1)	2)	3)	4)	5)
L.GTFP	—	0.186***	0.276***	0.156***	0.0389***
	—	(0.0203)	(0.0138)	(0.0197)	(0.0726)
L2.GTFP	—	−0.334***	−0.612***	−0.335***	−0.358***
	—	(0.0165)	(0.0164)	(0.0368)	(0.0736)
lndf	0.0640***	0.0362***	0.0262***	0.0168**	0.057***
	(0.0178)	(0.0030)	(0.0053)	(0.0073)	(0.0534)
er	−0.0472**	—	−0.0623***	−0.0602***	−0.121***
	(0.0641)	—	(0.0054)	(0.0079)	(0.0117)
lndf × er	0.253**	—	—	0.693***	0.520***
	(0.103)	—	—	(0.0336)	(0.0818)
lnpgdp	0.0984**	—	—	—	0.0480**
	(0.0705)	—	—	—	(0.0688)
indus	0.498**	—	—	—	1.206***
	(0.216)	—	—	—	(0.288)
lninnov	0.115***	—	—	—	0.225***
	(0.0231)	—	—	—	(0.0196)
green	0.992**	—	—	—	1.454**
	(0.455)	—	—	—	(0.694)
open	−0.233***	—	—	—	−0.276***
	(0.0675)	—	—	—	(0.0936)
_cons	1.916***	1.438***	2.034***	1.337***	1.830***
	(0.243)	(0.0319)	(0.0194)	(0.0287)	(0.383)
AR(1)-P	—	0.042	0.033	0.043	0.031
AR(2)-P	—	0.386	0.549	0.536	0.793
Sargan-P	—	0.845	0.973	1.000	1.000
N	300	210	210	210	210

Note: Values in parentheses are standard errors. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

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environmental regulation index (*er*), which avoids the bias of the single indicator method.

3.3.3 Control variables

To mitigate the estimation bias caused by omitted variables, this paper combines macroeconomic theory and the variables considered by relevant scholars in the research process (Wu et al., 2020; Zhao and He, 2022; Zhao et al., 2022a; Zhao et al., 2022b), then selects five indicators of economic development level (*gdp*), industrial structure (*indus*), technological innovation level (*innov*), greening level (*green*), and openness to the outside world (*open*) as control variables. Economic development and green development are closely related, and this paper expresses the level of regional economic development in terms of real GDP *per capita* calculated in constant prices in 2010. Numerous studies have shown that industrial structure is one of the important factors affecting green development. Therefore, this paper uses the ratio of the output value of secondary industry to GDP to indicate the status of industrial structure. Technological innovation can effectively improve the production efficiency of traditional industries, promote the progress of environmental protection technology, improve the green manufacturing capability of enterprises (Liu et al., 2022), and thus promote green development. This paper selects the number of domestic patent applications granted to measure the level of technological innovation. The greening level reflects the green development level of the region to a certain extent, and this paper measures the greening level of the region by the proportion of the greening coverage area of the built-up area to the total area of the built-up area. The level of external openness directly reflects the degree of connection between a country or region and foreign regional markets, which is conducive to promoting exchanges and cooperation among enterprises, and thus improving production efficiency and technological innovation. In this paper, we use the proportion of total import and export trade to GDP to measure the level of external openness. In order to narrow the scale between variables and improve the accuracy of the test results, the values of economic development level and technological innovation level are treated as logarithms in this paper.

3.3.4 Data sources

Given that the Peking University Digital Financial Inclusion Index has been measured since 2011, a total of 10 years of data from 2011–2020 is selected based on data availability. Since Tibet, Hong Kong, Macao, and Taiwan statistics are more seriously missing, we use the provincial panel data of 30 provinces as the basis for testing and analysis. The data are obtained from EPS database, CSMAR database, China Statistical Yearbook, and China Environmental Statistical Yearbook. Table 1 shows the definition and description of each variable.

4 Empirical analysis

4.1 Impact of digital finance and environmental regulation on green development efficiency

In this paper we adopt Arellano-Bond's approach, the dynamic differential GMM model, use the lagged terms of the explanatory variables as instrumental variables to solve the model endogeneity problem, and use STATA16.0 to estimate the impact relationship between digital finance, environmental regulation, and green development efficiency. Two conditions are required for the application of the two-step differential GMM model: first, there is first-order autocorrelation in the random disturbance terms, but not second-order or higher-order autocorrelation; second, there is no over-identification of instrumental variables. The estimation results are in Table 2. AR 1) is significant at the 5% level, but AR 2) is not significant, which is consistent with condition one. The Sargan test results show that the *p*-value is greater than 0.1, which is not significant, indicating that all instrumental variables are valid, which is consistent with condition two.

Table 2 reports the estimation results for the full sample, where column (1) shows the estimation results using the fixed effects model and columns (2) to (5), using the differential GMM estimation method and adding variables column by column. The results in Table 2 denote that digital finance and environmental regulation have a significant

TABLE 3 Sub-dimensional regression results.

Variable	(1)*GTFP*	(2)*GTFP*	(3)*GTFP*
	cov	*deep*	*dif*
L.GTFP	0.0293	0.0433	0.0909
	(0.147)	(0.0512)	(0.112)
L2.GTFP	−0.452***	−0.248**	−0.219*
	(0.110)	(0.0967)	(0.132)
er	−0.204***	−0.0601***	−0.264***
	(0.0421)	(0.0221)	(0.0291)
lncov	0.197***	—	—
	(0.0350)	—	—
lncov × er	0.326**	—	—
	(0.166)	—	—
lndeep	—	0.0767***	—
	—	(0.0163)	—
lndeep × er	—	0.678***	—
	—	(0.0458)	—
lndig	—	—	0.126***
	—	—	(0.0120)
lndig × er	—	—	0.724***
	—	—	(0.159)
controls	Yes	Yes	Yes
_cons	2.795***	3.984***	2.938***
	(0.461)	(0.219)	(0.343)
AR(1)-P	0.018	0.036	0.040
AR(2)-P	0.432	0.903	0.449
Sargan-P	1.000	1.000	1.000
N	210	210	210

Notes: Values in parentheses are standard errors. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

TABLE 4 Endogeneity test: IV-2SLS.

Variable	First stage	Second stage
	df	*GTFP*
Internet penetration rate	0.0265***	—
	(0.0031)	—
df	—	0.0994***
	—	(0.0314)
controls	Yes	Yes
Adj-R^2	0.714	0.821
N	300	300

Notes: Values in parentheses are standard errors. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 5 Robustness tests.

1) System GMM		2) Substitution of explanatory variables	
L.GTFP	0.289***	*L.GTFP*	0.558***
	(0.099)		(0.062)
L2.GTFP	−0.768***	*L2.GTFP*	−0.660***
	(0.074)		(0.067)
lndf	0.194***	*lndf*	0.184***
	(0.029)		(0.045)
er	−0.174***	*er1*	−0.044***
	(0.016)		(0.008)
lndf × er	0.582***	*lndf × er1*	0.331***
	(0.142)		(0.081)
controls	Yes	*controls*	Yes
_cons	0.103***	*_cons*	3.111***
	(0.273)		(0.820)
AR(1)-P	0.037	*AR(1)-P*	0.005
AR(2)-P	0.278	*AR(2)-P*	0.178
Sargan-P	1.000	*Sargan-P*	1.000
N	240	*N*	210

Notes: Values in parentheses are standard errors. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

impact on green development efficiency, indicating that digital finance and environmental regulation play an important role in the green development process.

Considering the problem of "tightening 1 year and loosening the other" in the implementation of environmental regulatory policies and institutions, the model is estimated using the lagged one-period and lagged two-period green development efficiency as instrumental variables, as shown in Table 2. The coefficient of green development efficiency of the first lag is significantly positive in the current period, which means that the green development efficiency of the previous period has a significant effect on the green development efficiency of the current period. In contrast, the green development efficiency of the second-period lag has a significantly negative impact on the green development efficiency of the current period, which means that the green development efficiency of the second-period lag inhibits the green development efficiency of the current period. This indicates that the improvement of green development efficiency in the previous period improves the ecological environment. However, due to the implementation of environmental regulation policies with a certain lag, environmental regulation has not yet shown its impact effect, and the government chooses to continue to implement the environmental regulation policies in the previous period. Moreover, green development efficiency in the second lag has a suppressive effect on the current period, which means that the high intensity of environmental regulation suppresses the green development efficiency, and due to the competitive pressure, the government has to choose to relax the intensity of environmental regulation and increase economic output, so as to win the competition among governments.

The effect of digital finance (*df*) on green development efficiency is significantly positive, which indicates that the development of digital finance has a significant contribution to local green development efficiency. Thus, Hypothesis 1 is supported. Digital finance has strong green attributes, and its natural advantages of inclusiveness, efficiency, and convenience play a positive role in the process of enhancing green development efficiency. On the one hand, digital finance expands the boundary of financial services with modern digital technology, improves resource allocation efficiency, accurately identifies green projects through technical screening function, and directs resources to high-tech and innovative environment-friendly enterprises, thus increasing environmental benefits as a "blood transfusion" for enterprises. On the other hand, it stimulates green consumption demand and promotes the transformation and upgrading of green industries. Green consumption and green credit stimulate residents' demand for environmentally friendly products, spur industries to upgrade to green and environmental protection, improve the virtuous cycle of economy and environment, and promote green development.

The effect of environmental regulation (*er*) on green development efficiency is significantly negative, which implies that environmental regulation has a negative effect on the improvement of green development efficiency, which runs contrary to Hypothesis 2. The empirical findings indicate that the impact of environmental regulation has not yet crossed the Porter's inflection point; i.e., the negative effect of compliance cost brought by environmental regulation to enterprises has not yet jumped to the technological innovation compensation positive effect. The possible reason is that China's environmental regulations are mostly based on emission constraints and pollution control, forcing enterprises to increase pollution treatment and ecological protection expenditures, but China is also mainly a heavy industry and manufacturing economy that is subject to high levels of environmental regulations and large compliance costs. Only proper environmental regulations can promote enterprises to improve energy efficiency, innovate production processes and environmental protection technologies, and continue to play the innovation compensation effect in order to enhance the efficiency of green development.

The synergistic effect of digital finance and environmental regulation (digital finance and environmental regulation interaction term *df***er*) on green development efficiency is significantly positive, which indicates that the interactive effect of digital finance and

environmental regulation has a positive impact on green development efficiency improvement. Thus, Hypothesis 3 is supported. Digital finance can alleviate the financing constraints arising from environmental regulations and to a certain extent weaken the negative impact of environmental regulations on green development efficiency. Local governments also need to use digital finance to guide the flow of resources and support the innovation and application of production technology and pollution control technology when using environmental regulations to push enterprises to green transformation and upgrading. Therefore, the synergy between digital finance and environmental regulation can effectively improve the efficiency of regional green development.

4.2 Analysis of the impact of interaction between sub-dimensions of digital finance and environmental regulation on green development efficiency

To further explore the impact of the interaction between the dimensions of digital finance and environmental regulation on the efficiency of green development, this paper estimates the three sub-dimensions of digital finance. The results appear in Table 3. As can be seen from the table, all three dimensions of digital finance are significant at the 1% level with positive coefficients, indicating that the breadth of coverage, depth of use, and digitization of digital finance significantly enhance green development efficiency. In terms of the magnitude of the coefficients, the degree of influence of the three sub-dimensions on green development efficiency is: breadth of coverage > digitalization > depth of use. The intensity of environmental regulation has a negative effect on green development efficiency, but its interaction with the digital finance sub-dimension has a significant positive effect on green development efficiency.

4.3 Endogenous discussion

An underlying assumption of the above analysis is the premise that digital finance is an exogenous variable. Although this paper uses a dynamic panel GMM model to reduce the problem of endogeneity among variables, there is still reverse causality leading to endogeneity bias in the model estimation process. Therefore, this paper uses the Durbin-Wu-Hausman test for endogeneity of the core explanatory variables. The test results show that the p-value is less than 0.05, and digital finance is considered as an endogenous variable. In order to avoid the reverse causality of "the higher the efficiency of green development, the higher the degree of access to green financial resources and even digital financial development," in this paper we use the Internet penetration rate as an instrumental variable and adopt the 2SLS method to correct for the endogeneity of the model.

After controlling for the level of regional economic development, industrial structure, technological innovation, greening level, and openness to the outside world, there is no direct correlation between Internet penetration rate and green development, which satisfies the requirement of exogeneity. The use of instrumental variables needs to be tested for validity. First, the Keilbergen-Paap rk LM statistic is used for the non-identifiability test, and the result shows that the value of the statistic is 51.639 (p = 0.000), indicating that the instrumental variables can be effectively identified. Furthermore, the Keilbergen-Paap rk LM statistic is used to test the validity of the instrumental variables. In the Keilbergen-Paap rk Wald F-statistic for weak instrumental variables test, the results show that the value of the statistic is greater than the critical value of 19.93 for Stock-Yogo at the 10% significance level, indicating that there are no weak instrumental variables. The results in Table 4 indicate that digital finance can still significantly improve the efficiency of green development after accounting for endogeneity issues.

4.4 Robustness test

To test the robustness of the model estimation results, this paper uses the systematic GMM estimation method and substitution of core explanatory variables to test the robustness of the above findings.

1) Systematic GMM method. Compared with differential GMM, the advantage of systematic GMM is that it can improve the efficiency of estimation and reduce the estimation error. Therefore, this paper uses the systematic GMM model to conduct robustness tests on the data, as shown in Table 5(1). The test results are consistent with those of the differential GMM model.
2) Replacement of core explanatory variables. In order to test the robustness of the results, this paper adopts another method to measure environmental regulation and selects the proportion of industrial pollution control investment to GDP to measure the intensity of environmental regulation in each province. The results of the robustness test by the above method are basically consistent with a previous paper, which indicates that the empirical results of this study are robust and reliable.

5 Conclusion and policy recommendations

Based on identifying the mechanisms of digital finance and environmental regulation on green development efficiency, this research measures green development efficiency using the directional distance function and Malmquist-Luenberger index based on 30 provinces' panel data in China from 2011 to 2020. The relationship among digital finance, environmental regulation and green development efficiency is empirically analyzed through a dynamic panel GMM model. The main findings are as follows. 1) Digital finance and its three sub-dimensions have a catalytic effect on the improvement of green development efficiency. 2) Environmental regulation has not yet crossed Porter's inflection point and still has a suppressive effect on green development efficiency. 3) The interaction between digital finance and environmental regulation has a positive effect on the improvement of green development efficiency. 4) The interaction between digital finance and environmental regulation has a positive impact on the improvement of green development efficiency, indicating that digital finance can alleviate the financing constraints arising from environmental regulation and to some extent weaken the negative effect of environmental regulation on green development efficiency.

Based on the above research findings, we propose the following policy recommendations.

1) Give full play to the active role of digital finance in ecological and environmental governance. First, the government should rely on modern digital technology to accurately screen green, clean, and environmental protection enterprises and projects, guide financial resources to high technology, high value-added, and other green industries, appropriately finance high pollution and high energy consumption enterprises, accelerate the layout of the green industry chain, and force the green transformation and upgrading of industries. Second, the relevant authorities should pus to build a diversified digital financial platform, carry out digital financial service model innovation, integrate social idle funds, give full play to the optimal allocation of resources in environmental protection, break the stratification of financial resources mobility, and make reasonable use of the government's "visible hand" and the market's "invisible hand". Third, efforts should be geared to giving full play to the optimal allocation of resources in environmental protection, breaking the stratification of financial resource liquidity, building a government-market dual-track parallel mechanism, and promoting the synergy of digital finance and environmental regulation to promote green development.
2) Optimize the top-level design of environmental regulation and establish a reasonable, scientific, and flexible environmental regulation system. First, China should formulate differentiated and diversified environmental regulation policies according to local conditions. There are significant regional differences in the impact of environmental regulation on the efficiency of green development, and the country should combine the characteristics of economic and environmental resource endowments of each region to formulate environmental regulation policies that are compatible with the characteristics of industries. Second, the government should improve every detail of environmental regulations from their introduction to their implementation to avoid the phenomenon of "loud thunder but little rain" in their implementation. At the same time, the process of implementing environmental regulation policies should also avoid brutal policy implementation methods such as "one size fits all" and "one stop". Third, to reduce the frequency of environmental regulation policy adjustment, some regions in the pursuit of economic development of environmental regulation have implemented a policy of "a year tight and a year loose", resulting in serious slowdown of the green development process. Thus, local governments should develop a long-term environmental regulation system and implement strict and appropriate intensity of environmental regulation, in order to play a positive role of environmental regulation on green development efficiency. Only in this way can environmental regulations really exhibit a positive role in the efficiency of green development.
3) Actively encourage and support the R&D and application of green innovative technologies in enterprises to provide endogenous drive for green development. The authorities should tighten the direction of green and low-carbon development, set up advanced green and low-carbon technology R&D teams, break down technical barriers, increase support for R&D of key core technologies, promote the output and application of low-carbon technology achievements, and promote the process of green development. The global trend is low-carbon transition, low-carbon development capability, and advanced low-carbon technology, which represent international competitiveness. Therefore, supervising the R&D and application of low-carbon technologies is beneficial for China to seize the high point of future world green market competition and lead the trend of low-carbon economic development in the world.

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

YH: conceptualization, software, resources, writing—original draft preparation, conceptualization, methodology, data curation; YL: validation, investigation; QW: validation, validation, writing—reviewing and editing, 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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The impact of listed companies' participation in targeted poverty alleviation on financing constraints: Mediating effect based on policy resources

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This article aims to explore the inner relationship between targeted poverty alleviation and financing constraints of listed companies, and further reveal the underlying impact mechanism. Based on the data of listed companies in Shanghai and Shenzhen A-share main board participating in targeted poverty alleviation from 2017 to 2020, graded response models and mediation models are conducted. From the perspective of resource motivation, the study examined the relationship between the investment in targeted poverty alleviation and financing constraints of listed companies and introduces policy resources as mediator variable to reveal the underlying mechanism. The study found that the participation of listed companies in targeted poverty alleviation can significantly ease financing constraints, and policy resources can play an intermediary effect in the process. For enterprises with different equity nature, in state-owned enterprises, policy resources play a small intermediary role between poverty alleviation inputs and financing constraints. Meanwhile, in non-state-owned enterprises, government subsidies play a significant intermediary role, and tax incentives play a small intermediary role. In response to this, policy suggestions such as improving the disclosure of poverty alleviation information, expanding policy preferences, and increasing poverty alleviation subsidies have been suggested.

KEYWORDS

targeted poverty alleviation, listed companies, policy resources, financing constraints, mediator effect

1 Introduction

In recent years, corporate social responsibility has attracted more and more attention. The Chinese President, Xi Jinping, pointed out that only caring wealth is truly meaningful wealth, and only companies that actively undertake social responsibilities are the most competitive and vital companies. Undertaking social responsibility requires enterprises to supervise and restrict their own behavior, and pay attention to serving the society while creating profits. The pyramid model proposed by Carroll (1991) divided corporate social responsibility into economic responsibility, legal responsibility, ethical responsibility and charitable responsibility. Elkington (1998) proposed that corporate behavior should meet the economic bottom line, social bottom line and environmental bottom line. So far, fulfilling

social responsibility has become a general consensus. Ensuring corporate benefits and employee rights, participating in public welfare activities and social construction, environmental protection, among others; are the basic ways for enterprises to assume social responsibility. Specifically, contrary to extensive poverty alleviation, targeted poverty alleviation is defined as a poverty control method that uses scientific and effective procedures to accurately identify, assist and manage the targets of poverty alleviation in accordance with the environment of different poverty-stricken areas and the conditions of different poverty-stricken farmers. Enterprise participation in targeted poverty alleviation has been an important social responsibility in the context of the new era. It refers to the charitable behavior of enterprises freely and voluntarily using their disposable resources to relieve the poor under the guidance of government departments (Yang and Cheng, 2020). Listed companies are an important participant in China's poverty alleviation work and have played an important role in the process of eliminating absolute poverty. According to the white paper on consolidating poverty alleviation and promoting rural revitalization by Chinese listed companies, since putting forward the targeted poverty alleviation strategy, many listed companies in China have carried out targeted assistance to poor areas. According to the annual report of A-share listed companies in 2020, a total of 1,514 listed companies have disclosed that they have participated in poverty alleviation and rural revitalization. Out of these companies, 1,244 have capital investment, with a total poverty alleviation investment of 88.998 billion yuan, and have achieved remarkable results in industrial support, employment and financial support. These enterprises integrate market resources through their own advantages, drive regional development with their market experience, complement each other's advantages with the government's poverty alleviation, boost the development of China's poverty alleviation cause and promote the realization of common prosperity. These companies have specific motivations for participating in targeted poverty alleviation, and they can also bring specific benefits to them. Existing research shows that listed companies have three motivations for participating in targeted poverty alleviation: 1) Political motivation: in order to maintain and strengthen political connections, listed companies are more willing to fulfill their social responsibilities for targeted poverty alleviation (Yang and Cheng, 2020); 2) Economic motivation: in order to enhance the corporate image, pursue more hidden benefits, and then improve its profitability (Wang, 2020); 3) Resource motivation: in order to obtain more resources, such as government subsidies, tax incentives, lower financing costs, among others (Wang et al., 2020). In terms of economic consequences, the participation of listed companies in targeted poverty alleviation can significantly improve corporate financial performance (Zhang and Xing, 2019) and effectively ease their own financing constraints (Yi et al., 2020). Based on this motivation, enterprises will participate in poverty alleviation through industrial development, transfer of employment, relocation, ecological protection, education, medical treatment and other ways to increase income for the poor, drive industrial development and economic growth in poor areas, and achieve a win-win situation for enterprise interests, social benefits and economic benefits.

However, the ways in which companies participate in poverty alleviation are diversified, and a single-dimensional measurement is often difficult to reflect the comprehensive performance of poverty alleviation investment. For instance, some scholars regard industrial targeted poverty alleviation investment as enterprise poverty alleviation investment (Yin et al., 2021). Therefore, this article uses the item response theory (IRT) to measure poverty alleviation investment to improve its comprehensiveness and accuracy. In addition, as for the discussion of the mechanism behind the effect of poverty alleviation, scholars pay more attention to audit quality, financial performance, and enterprise innovation. For example, Guo et al. (2022) demonstrated that enterprises' participation in targeted poverty alleviation has significantly improved audit quality; Zhang and Xing (2019) have proved that enterprises' increasing investment in targeted poverty alleviation has a significant effect on improving their financial performance. Liu et al. (2020) found that the targeted poverty alleviation behavior of enterprises will improve the innovation output of enterprises, but the quality of enterprise innovation will decline under the same structure. However, existing research seldom pays attention to financing constraints. In view of this, this article has compiled the data of the Shanghai and Shenzhen A-share main board listed companies that participated in targeted poverty alleviation from 2017 to 2020. The investment in targeted poverty alleviation was regarded as a latent variable, and the item response theory model was used to comprehensively measure various poverty alleviation investments. From the perspective of resource motivation, using policy resources as an intermediary variable, we thoroughly examined the impact of targeted poverty alleviation investment on financing constraints. In the same vein, we reveal the mechanism and consequences of listed companies' participation in targeted poverty alleviation and provide theoretical and practical evidence for deepening listed companies' participation in relative poverty governance in the future.

The Item Response Theory (IRT) has a long history of application in educational testing and psychology, and is increasingly being used in economics and social sciences to infer potential characteristics. Currently, IRT models are used to study cognitive abilities, mental concepts, personality characteristics, attitudes, quality of life, patient satisfaction, and other potential attributes that cannot be directly measured. Recently, research in the fields of economics and social sciences has used this method to construct indexes that capture various potential characteristics. For example, Cappellari and Jenkins (2007) used information about family characteristics and the individual's perception of purchasing specific items to construct a household poverty index; Ødegaard and Roos (2015) used the answers to health status and psychosocial environment questions to construct labor quality indicators; Pericoli et al. (2015) estimated the social capital index based on the answers to the questions, which indicate the degree of social capital to social networks, citizen participation, and neighbor relations. Abdul-Salam and Phimister (2017), and Gao and Niu (2019) constructed an IRT model to accurately estimate the ability of farmers to obtain information. Peng and Zhu (2019) measured consumer objective and supervisory financial literacy index based on IRT. Li (2020) employed the grade response model in item reflection theory to scientifically measure the concept of rights, authority and other complex political and psychological concepts. The basic idea

of the IRT model used in these studies is that there are some potential characteristics or abilities, and the level of characteristics or abilities of the research object can be determined through observable responses, whether it is the answer to the question scale or the available data.

Many studies make use of the predicted potential index as an independent variable for their subsequent analysis. For example, Ødegaard and Roos (2015) used predictive values of potential labor quality in a DEA study to explain the production efficiency of large Swedish companies. Pericoli et al. (2015) used their index to explain the impact of social capital on consumer insurance and income fluctuations. Gao and Niu (2019) used estimated information acquisition capabilities to study its impact on farmers' adoption of Green Control Technique (GCT). Li (2020) used the measured political psychology such as the concept of rights to study its influence on online political participation.

According to the definition of Fazzari et al. (1988), financing constraints refer to the situation where the external financing costs of the company are too high due to the incomplete market, and therefore the company's investment cannot reach the optimal level. The typical consequence of financing constraints is to make a significant change in the matching status of corporate investment risks and returns compared with the situation in a complete market. To put it simply, companies are restricted in their external financing. Rajan and Zingales (1995) found that in the financing process, companies will cause "principle-agent" and "adverse selection" problems due to the existence of information asymmetry in the market. This leads to high external financing costs in the market and can only rely on internal funds with lower financing costs. However, internal funds are often very limited, so companies will be unable to meet financing needs due to the inability to pay high external financing costs. This indicates that companies are subject to financing constraints.

Current research reveals that financing constraints are mainly affected by the following factors: firstly, financial environment. In a sound financial environment with open markets, complete systems, and high resource allocation efficiency, corporate financing is easier and more convenient. Financial reform can promote the efficiency of the capital market, thereby alleviating the financing constraints faced by enterprises (Claessens and Laeven, 2003). Baum et al. (2011) inferred that the financial environment plays a vital role in reducing the barriers to external market financing, and that financing constraints are less in a good financial environment. Cheng et al. (2012) found that the opening of the capital market has a certain effect on alleviating financing constraints. Similarly, Wei et al. (2014) found that the optimization of the financial environment can effectively alleviate corporate financing constraints. Secondly, political connection. The government tends to favor politically connected companies and give them better credit resources and financing platforms. Cull et al. (2015) believe that political connections play an important role in explaining the financing conditions of Chinese companies, and political connections can significantly reduce financing constraints. Yu et al. (2012) found two mechanisms by which political connections can ease financing constraints. One of the mechanisms involves the use of political connections as a signal to reduce the information effect of information asymmetry. The other mechanism is the resource effect, this involves increasing the ability to obtain resources through political connections. Thirdly, internal factors of the enterprise. These include credit record, business performance, ownership property, ownership concentration, profitability, among others. Pagano et al. (1998) found that a company with a better credit record has a better reputation, which is conducive to the alleviation of financing constraints. Similarly, Cull and Xu (2003) believe that the better the business performance of the company, the more helpful it is to stabilize the bank's expectations of its future cash flow, thereby making it easier for the company to obtain bank loans and alleviating financing constraints. In addition, Faccio (2006) believes that compared with private enterprises, state-owned enterprises face less financing constraints. In the same vein, Wang and Zhao (2010) found that the higher the ownership concentration, the lower the capital adequacy ratio, and the better the profitability, the smaller the financing constraints of companies. Moreover, from a geographical point of view, listed companies in the eastern region face smaller financing constraints than those in the central and western regions. Fourthly, information disclosure. Some scholars have found a correlation between information disclosure and the cost of capital. The more information disclosed by a company, the lower the cost of capital (Diamond and Verrecehia, 1991; Botosan, 1997; Healy and Palepu, 2001; Verrecchia, 2001; Zhang and Lv, 2007) degree of information asymmetry and ease financing constraints. In addition, they contend that the higher the market's attention to companies, the more advantageous the company's information mining and dissemination. This further reduces information asymmetry significantly thereby reducing corporate financing constraints. However, Qian et al. (2016) found that the disclosure of corporate social responsibility information has a negative effect on financing constraints. They also assert that the accounting conservatism of a company has a negative effect on financing constraints, and the roles of the two play an alternative relationship.

Corporate financing constraints are affected by many parties, of course, including social responsibility behaviors. According to existing research, investors are more inclined to invest funds in enterprises that fulfill social responsibilities (Roberts and Dowling, 2002; Baron, 2007), and fulfilling social responsibilities can alleviate financing constraints (Godfrey, 2005). Richardson and Welker (2001) found that corporate disclosure of social responsibility information can help deliver positive information to the market, reduce information asymmetry between investors and operators, reduce investors' risk of predicting corporate-related financial information, thereby reducing capital costs and alleviating financing constraints. Similarly, Dhaliwal et al. (2011) found that companies can reduce the degree of information asymmetry by disclosing social responsibility information reports, thereby reducing their financing costs. In terms of the social responsibility of poverty alleviation, many scholars have found that enterprises' participation in targeted poverty alleviation can ease financing constraints. For instance, Deng et al. (2020) used A-share listed companies as a research sample and found that companies actively carrying out targeted poverty alleviation activities can effectively alleviate their own financing constraints. In the same vein, Wang and Wang (2020) found that companies' participation in targeted poverty alleviation and political connections can alleviate financing constraints, and the two have a synergistic effect on the impact of financing constraints.

The contributions of the research are as follows: First, there have been documents discussing the motivations and economic consequences of enterprises participating in precision poverty

alleviation. When it comes to the calculation of precision poverty alleviation investment, it uses the absolute number of inputs or the proportion of relative assets and income, among others. However, the way in which each enterprise participates in poverty alleviation is different, and the above methods cannot be used to scientifically compare poverty alleviation investment. This article proposes a method for measuring poverty alleviation investment based on the Item Response Theory (IRT), which is more scientific and comparable. Second, the existing literature discussing the relationship between targeted poverty alleviation by enterprises and financing constraints mainly focuses on direct impacts. From the perspective of resource motives, this article adds political resources as an important factor to examine the reasons behind participating in poverty alleviation for enterprises to ease financing constraints mechanism. Finally, based on the conclusion that enterprises' participation in targeted poverty alleviation will alleviate financing constraints, and policy resources play an intermediary role in it, this article puts forward suggestions to improve the disclosure of poverty alleviation information, expand policy preferences, and increase poverty alleviation subsidies. This will contribute to the government's further optimization of the social responsibility disclosure system and regulatory mechanism, and help enterprises to actively carry out targeted poverty alleviation activities and disclose relevant information.

The remainder of this article is organized as follows. The "Literature Review" section reviews relevant literature. The section on "Theoretical Analysis and Research Hypothesis" outlines the relationship among listed companies' targeted poverty alleviation, policy resources and financing constraints, and proposes hypotheses. The "Research Design" section describes the main variables and constructs the research model. The "Empirical Analysis" section examines the relationship between the investment in targeted poverty alleviation and financing constraints of listed companies, and introduces policy resources as an intermediary variable. It also highlights the underlying mechanism and further reveals the heterogeneity of poverty alleviation among enterprises of different property right. Finally, the article provides policy recommendations based on the research conclusion.

2 Theoretical analysis and research hypothesis

2.1 Targeted poverty alleviation and financing constraints

All listed companies face financing constraints, and information asymmetry is one of the important factors. According to the signaling theory, in the case of information asymmetry, well-run companies will transmit good news to the outside world, thereby attracting investors. Due to the limited resources of enterprises, when enterprises invest more resources in poverty alleviation, less resources will be used in the production and operation activities of enterprises, which may cause the decline of enterprise benefits and cause losses to stakeholders. However, companies actively fulfilling their social responsibilities for poverty alleviation can send a positive signal to the outside world, because poverty alleviation requires a lot of manpower and material resources to demonstrate corporate strength. This strengthens the willingness of stakeholders to provide resources to the enterprise and alleviates the problem of information asymmetry. At the same time, according to the Opinions on Giving Play to the Role of Capital Market to Serve the National Poverty Alleviation Strategy issued by the CSRC in 2016, the Shanghai Stock Exchange and Shenzhen Stock Exchange successively issued a notice on further information disclosure of poverty alleviation work, requiring listed companies to fully disclose relevant information such as poverty alleviation investment and poverty alleviation effect. The Notice on Improving the Information Disclosure of Listed Companies' Performance of Poverty Alleviation Responsibilities issued by the Shanghai Stock Exchange in 2019 clearly stipulates that listed companies should fully disclose the specific situation of the company's performance of its social responsibility for targeted poverty alleviation during the reporting period. Therefore, participation in poverty alleviation activities must be disclosed in the important matters chapter of the company's annual report. This can establish a good social image for the company and improve its reputation, thereby effectively reducing the information asymmetry between the company and the outside world, and win the recognition by the investors, creditors and other stakeholders. This reduces the possibility and cost of negative events, thereby reducing corporate risks (Jo and Na, 2012). In short, participating in targeted poverty alleviation can improve confidence communication with the outside world, enhance the company's image and reputation, and thereby increase the funding providers' confidence in corporate financing. Studies have shown that companies with better social responsibility performance face lower financing constraints, and the transparency of corporate social responsibility performance is of great significance in reducing corporate financing constraints (Cheng et al., 2014). As a result, companies can obtain loans more easily from banks and other creditors. Although fulfilling social responsibilities will bring some extra costs to enterprises, it will also bring high-quality business environment, reduce costs in some aspects, and leave good social credit for enterprises (Wang et al., 2022). Based on this, this study formulates the first hypothesis as (Figure 1).

H1: The more a listed company invests in targeted poverty alleviation, the more it can ease financing constraints.

2.2 Targeted poverty alleviation and policy resources

In line with the resource dependence theory, companies need to find a way to obtain key resources in a stable manner. Political resources, including the government's disposable financial funds, land and policies, as the key resources for the survival and development of enterprises, have a positive impact on the value of enterprises (Li et al., 2015). These key resources are usually allocated by the government, consequently, companies have certain motivations to respond to government policy guidelines. Participating actively in the government's targeted poverty alleviation work facilitates enterprises and the government to establish close ties, and they are willing to bear some costs in exchange for more resources (Fan et al., 2013). Policy resources,

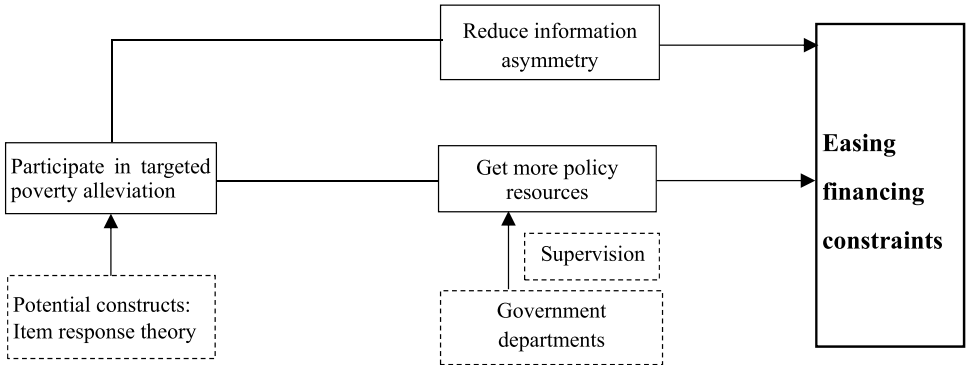

FIGURE 1
The research framework of this study.

as an important part of political resources, also play a key role for enterprises, especially the two major policies of government subsidies and tax incentives. In order to compensate enterprises for the cost of fulfilling their social responsibilities, the government usually adopts subsidies and preferential tax policies to increase the enthusiasm of enterprises to participate in targeted poverty alleviation. Yan and Tang (2020) found that the participation of listed companies in targeted poverty alleviation can significantly increase government subsidies. Similarly, Wang et al. (2020) believe that enjoying tax incentives is a major driving force for listed companies to participate in targeted poverty alleviation. Based on this, this study formulates the second hypothesis as (Figure 1).

H2: The more a listed company invests in targeted poverty alleviation, the more policy resources it can obtain.

2.3 Targeted poverty alleviation, policy resources and financing constraints

The signaling theory states that listed companies hope to send positive signals to the outside world by fulfilling their social responsibilities for poverty alleviation, reducing information asymmetry, and thereby reducing their financing constraints. However, precise poverty alleviation information is generated by companies, investors will question the authenticity of the information. However, due to the differences in the nature of enterprises, there are also differences in the possibility of being questioned. For state-owned enterprises, they have natural political advantages and their social responsibilities are more based on social obligations (Yi et al., 2020), and the intensity of internal audit and government supervision is slightly higher than that of non-state-owned enterprises. Therefore, investors rarely question the authenticity of information when participating in targeted poverty alleviation. Relatively speaking, non-state-owned enterprises tend to obtain more political resources when participating in targeted poverty alleviation that investors will be more suspicious of the authenticity of their information disclosure, such as questioning if companies are deliberately concealing unfavorable information for their own benefit and inflating investment in poverty alleviation. At the same time, the government's policy resources for enterprises (such as government subsidies or tax incentives) can constitute an objective supervision mechanism, which is conducive for companies to send more true and objective positive signals to the outside world to enhance creditors' confidence, thereby reducing financing constraints. Wu (2019) believes that government subsidies can eliminate the information asymmetry between the supply and demand sides of funds to a certain extent, and reduce corporate financing constraints. Yu and Yang (2016) found that small and medium-sized enterprises with more financing, and tax incentives; have a significant positive effect on corporate financing. Based on this, this study formulates the third hypothesis as (Figure 1).

H3: Policy resources play an intermediary role between the targeted poverty alleviation and financing constraints of listed companies.

3 Research design

3.1 Sample selection and data sources

The poverty alleviation data used were derived from the Chinese Research Data Services (CNRDS). The selected data is the amount of each sub-investment in the precision poverty alleviation table disclosed in the annual report of the Shanghai and Shenzhen A-share listed companies participating in precision poverty alleviation from 2017 to 2020. Other financial data comes from China Stock Market and Accounting Research Database (CSMAR). The data were screened according to the purpose of the research ensuring the exclusion of: 1) listed companies without specific investment amount; 2) listed companies in the financial industry. Due to the particularity of the financial industry, it has special sub-inputs, such as the amount of loans for targeted poverty alleviation projects, which are quite different from other industries; 3) ST and *ST listed companies with abnormal financial indicators; 4) samples that have been listed for less than 3 years and whose variables are missing. In addition, in order to eliminate the influence of extreme

TABLE 1 Descriptive statistics of listed companies participating in targeted poverty alleviation (Unit: ten thousand Yuan).

Projects	2017	2018	2019	2020
Poverty alleviation by developing competitive industries	3,066.729	2,889.082	3,536.941	2,996.297
Poverty alleviation by finding jobs elsewhere	132.673	129.573	108.676	167.708
Poverty alleviation by relocation	172.390	601.833	773.400	0.000
Poverty alleviation by improving education	118.819	129.835	216.727	269.859
Poverty alleviation by providing better healthcare	402.409	541.756	335.038	787.963
Poverty alleviation by better ecological protection	1,290.117	706.459	220.384	205.342
Poverty alleviation by securing basic needs through social security	84.113	83.955	84.519	102.959
Social assistance in poverty alleviation	372.962	293.565	851.337	443.761
Other projects	157.751	388.056	457.994	373.164

values, this study winsorizes all the continuous variables at 1% and 99% level. After the screening, 1,036 research samples were finally determined, with a total of 4,144 annual data.

3.2 Definition of variables

3.2.1 Dependent variable

In this study, financing constraints is regarded as the dependent variable. Previous studies have shown that there are various methods that can be used to measure financing constraints. The more representative methods include KZ index (Kaplan and Zingales, 1997), WW index (Whited and Wu, 2006) and SA index (Hadlock and Pierce, 2010). The Tobin Q value in the KZ index, which reflects the investment opportunities of enterprises, is prone to large measurement errors, resulting in inaccurate measurement of corporate financing constraints. Compared with the KZ index, the WW index excludes Tobin's Q value, and in addition to the financial characteristics of the company itself, it also considers the characteristics of the industry in which it is located, which has broader economic significance. The specific model is as follows:

$$WW_{it} = -0.091^{*}CF_{it} - 0.062^{*}DivPos_{it} + 0.021^{*}TLTD_{it} - 0.044^{*}Size_{it} + 0.102^{*}ISG_{it} - 0.035 \times SG_{it} \quad (1)$$

Among them, CF_{it} is the net cash flow generated by operating activities divided by total assets; $DivPos_{it}$ is a dummy variable of whether the company pays cash dividends, if it is paid, it is taken as 1, otherwise it is taken as 0; $TLTD_{it}$ is long-term liabilities divided by total assets; $Size_{it}$ is the natural logarithm of total assets; ISG_{it} and SG_{it} represent the sales growth rate of the industry and the company, respectively. The larger the WW index, the greater the financing constraints.

3.2.2 Explanatory variable

The explanatory variable in this study is the investment in targeted poverty alleviation. Its original data comes from nine targeted poverty alleviation projects (See Table 1 for mean value statistics). Due to the diversification of poverty alleviation investment categories, the units of various indicators are not the same, and there may be some problems in fitting the composite index. However, the project response theory is a potential variable estimation method considering the difference of project weights. This article regards poverty alleviation investment as a potential structure. First, we use the quartile method to process the itemized input of poverty alleviation samples in each year, and convert the ordinal variables of 0, 1, 2, 3, and 4 to facilitate the parameter estimation of the grade response model (GRM). Second, we use the Bayesian expectation posterior estimation method to estimate the latent investment in targeted poverty alleviation.

Assuming that θ_j is the real poverty alleviation investment of listed company j that cannot be directly observed, k is the poverty alleviation investment level of each sub-item i, and k = 0, 1, 2, 3, 4. In the grade response model, suppose P_{*ik} is the probability that the investment level of a listed company with poverty alleviation investment θ is not lower than k, and P_{ik} is the probability that the investment level of the listed company in the i sub-item is exactly k. The specific expression is as follows:

$$P_{ik} = P_{*ik} - P_{*ik+1} \quad (k = 0, 1, 2, 3, 4) \quad (2)$$

$$P_{*ik} = 1/\{1 + exp[-Da_i(\theta_j - b_{ik})]\} \quad (3)$$

Among them, D = 1.7, a_i is the degree of discrimination of the i sub-item, and b_{ik} is the difficulty value of k points for the i sub-item. According to the study (Yang et al., 2008), the value of the discrimination parameter a is between [0.3, 4], and the difficulty parameter of the item is moderate when the value range of b is in the range of [−4, 4]. The research results show that the discrimination parameter and the diversity parameter conform to the above range.

On the basis of parameter estimation, the Bayesian posterior expectation estimate is used to estimate the poverty alleviation investment θ_j, and the poverty alleviation investment corresponding to each listed company every year is obtained, and standardized processing is carried out.

Before parameter estimation, the single-dimension and local independence tests should be carried out. The single-dimensional test can be verified by factor analysis results. The results show that the characteristic roots of the first factor are 1.30, 1.33, 1.42, and 1.69 respectively from 2017 to 2020, and the characteristic roots of the second factor are 0.20, 0.17, 0.19, and 0.17 respectively. The

TABLE 2 Variables and definitions.

Type	Name	Abbreviation	Definition
Dependent variable	Financing constraints	WW	WW index
Independent variable	Investment in targeted poverty alleviation	Pov	According to the Graded Response Model (GRM)
Mediating variable	government subsidies	Sub	The natural logarithm of government subsidies
	tax incentives	Tax	(Nominal tax rate-actual tax rate) * total profit
Control variables	listing age	Age	Listing duration
	ownership concentration	Top	The largest shareholder's shareholding ratio
	asset-liability ratio	Lev	Liabilities/Total assets
	growth	Growth	(current operating income—last operating income)/last operating income
	cash flow	CF	Net cash flow from operating activities/total assets
	profitability	Roa	Net profit/Total assets
	capital expenditure rate	Capex	Cash paid to construct fixed assets, intangible assets and other long-term assets/Total assets

characteristic roots of the first factor are 6.5 times, 7.82 times, 7.47 times, and 9.94 times of the characteristic roots of the second factor, all of which are greater than 3, meeting the single-dimensional test. On the other hand, R software provides Q3 program for local independence inspection. The results show that the absolute value of the correlation coefficient of all poverty alleviation projects is less than 0.3, meeting the assumption of local independence.

3.2.3 Mediating variable

The mediating variable in this study is the policy resources. These are measured by the most intuitive performance of policy resources—government subsidies and tax incentives received. Among them, the government subsidy data adopts the "Extraordinary profit and loss—government subsidies included in the current profit and loss" disclosed in the notes to the annual report, and the logarithm is used for processing. Tax incentives mainly consider income tax incentives, using the difference between the nominal corporate income tax rate and the actual tax rate and multiplying the total profit, and standardizing the subsequent measurement.

3.2.4 Control variables

Based on the existing research in related literature, the following control variables are selected: listing age, ownership concentration, asset-liability ratio, growth, cash flow, profitability, capital expenditure rate, as well as the control the impact of the Year, Industry, and Area. The variables and definitions are shown in Table 2.

3.3 Model setting

According to Wen et al.'s (2004) method, when studying the mediation effect, the model is constructed as follows.

Model a:

$$WW_{it} = \alpha_1 Pov_{it} + \alpha_2 Age_{it} + \alpha_3 Top_{it} + \alpha_4 Lev_{it} + \alpha_5 Growth_{it} + \alpha_6 CF_{it} + \alpha_7 Roa_{it} + \alpha_8 Capex_{it} + Year + Industry + Area + \delta \quad (4)$$

Model b:

$$Sub_{it}/Tax_{it} = \beta_1 Pov_{it} + \beta_2 Age_{it} + \beta_3 Top_{it} + \beta_4 Lev_{it} + \beta_5 Growth_{it} + \beta_6 CF_{it} + \beta_7 Roa_{it} + \beta_8 Capex_{it} + Year + Industry + Area + \varphi \quad (5)$$

Model c:

$$WW_{it} = \gamma_1 Pov_{it} + \gamma_2 Sub_{it}/Tax_{it} + \gamma_3 Age_{it} + \gamma_4 Top_{it} + \gamma_5 Lev_{it} + \gamma_6 Growth_{it} + \gamma_7 CF_{it} + \gamma_8 Roa_{it} + \gamma_9 Capex_{it} + Year + Industry + Area + \delta \quad (6)$$

Model a is used to test the main effect of targeted poverty alleviation and financing constraints of listed companies. If the coefficient α_1 is significant, it means that the main effect exists. Therefore, Hypothesis 1 is valid. Model b is used to test the relationship between targeted poverty alleviation and policy resources of listed companies. If the coefficient β_1 is significant, it means that listed companies' participation in targeted poverty alleviation can affect the policy resources they obtain. Hence, Hypothesis 2 is valid. Finally, Model c is used to test the intermediary effect. If both γ_1 and γ_2 are significant, it indicates that policy resources have an intermediary role in the relationship between listed companies' targeted poverty alleviation and financing constraints. As a result, Hypothesis 3 is valid.

TABLE 3 Descriptive statistical results.

Variable	Observation	Mean	P25	P50	P75	SD	Min	Max
WW	4,144	−1.053	−1.100	−1.052	−1.002	0.073	−1.255	−0.835
Pov	4,144	0.173	0.000	0.121	0.283	0.192	0.000	1.000
Sub	4,144	16.663	15.877	16.901	17.870	2.536	0.000	20.834
Tax	4,144	0.355	0.337	0.344	0.354	0.105	0.000	1.000
Age	4,144	14.935	9.000	15.000	21.000	7.284	2.000	31.000
Top	4,144	0.348	0.227	0.323	0.450	0.153	0.091	0.750
Lev	4,144	0.457	0.311	0.459	0.597	0.190	0.077	0.866
Growth	4,144	0.157	−0.006	0.100	0.240	0.371	−0.539	2.414
CF	4,144	0.057	0.019	0.054	0.093	0.061	−0.102	0.239
Roa	4,144	0.043	0.016	0.037	0.068	0.056	−0.192	0.224
Capex	4,144	0.044	0.015	0.033	0.061	0.040	0.001	0.197

TABLE 4 Correlation analysis.

	WW	Pov	Sub	Tax	Age	Top	Lev	Growth	CF	Roa	Capex
WW	1										
Pov	−0.392***	1									
Sub	−0.360***	0.182***	1								
Tax	−0.242***	0.169***	0.100***	1							
Age	−0.232***	0.085***	0.001	−0.028*	1						
Top	−0.281***	0.107***	0.073***	0.121***	−0.010	1					
Lev	−0.426***	0.193***	0.188***	−0.034**	0.208***	0.045***	1				
Growth	−0.182***	−0.014	0.014	0.037**	−0.106***	0.033**	0.061***	1			
CF	−0.184***	0.079***	0.026*	0.108***	−0.029*	0.111***	−0.194***	0.029*	1		
Roa	−0.208***	0.014	0.010	0.252***	−0.110***	0.165***	−0.327***	0.240***	0.470***	1	
Capex	−0.013	0.057***	0.085***	0.061***	−0.167***	−0.010	−0.020	0.063***	0.201***	0.131***	1

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

3.4 Empirical analysis

3.4.1 Descriptive statistics and correlation analysis

From Table 3, the mean value of financing constraints (WW) is −1.053 indicating that the scale of enterprise financing constraints has small difference. The mean value of poverty investment of enterprises is 0.173, and the standard deviation is 0.192. It can be seen that enterprises participating in targeted poverty alleviation have a small difference in poverty alleviation investment. From the perspective of the main control variables, the average of government subsidies (Sub) is 16.663, the standard deviation is 2.536, the median is 16.901, the minimum value is 0, and the maximum value is 22.876, indicating that there are certain differences in government subsidies to enterprises (Sub). The average age of enterprises is 14.935, the standard deviation is 7.284, the median is 15.000, the minimum value is 2, and the maximum value is 31, indicating that there are differences in the age of enterprises listed (Age). The standards of other indicators are small, the maximum and minimum values conform to the distribution law, and there are no extreme values and abnormal values in the observation sample, all within reasonable scope.

From the results in Table 4, it can be seen that the correlation between the main variables is more consistent with the hypothesis, and Hypotheses 1, 2, and 3 can be initially verified. In addition, the absolute value of the correlation coefficient of each variable is 0.426 at the maximum, which does not exceed 0.6. The test results of the variance inflation factor show that the maximum value of VIF is 1.63 and the average value is 1.19, indicating that there is no serious multiple collinearity problem.

3.4.2 Regression results and analysis

Table 5 reports the regression results of the three models. The results of model a show that the regression coefficient of investment

TABLE 5 Regression results.

Variable	Model a	Model b		Model c	
	WW	Sub	Tax	WW(Sub)	WW(Tax)
Pov	−0.096***	1.894***	0.086***	−0.082***	−0.089***
	(0.004)	(0.200)	(0.008)	(0.004)	(0.004)
Sub				−0.007***	
				(0.000)	
Tax					−0.081***
					(-0.008)
Age	−0.001***	0.001	−0.000	−0.001***	−0.001***
	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)
Top	−0.062***	1.221***	0.039***	−0.053***	−0.059***
	(0.005)	(0.254)	(0.011)	(0.005)	(0.005)
Lev	−0.154***	3.878***	0.024**	−0.126***	−0.152***
	(0.005)	(0.235)	(0.010)	(0.005)	(0.005)
Growth	−0.027***	−0.058	−0.008*	−0.028***	−0.028***
	(0.002)	(0.105)	(0.004)	(0.002)	(0.002)
CF	−0.110***	−1.352*	−0.067**	−0.120***	−0.115***
	(0.015)	(0.709)	(0.030)	(0.014)	(0.015)
Roa	−0.364***	2.874***	0.520***	−0.343***	−0.322***
	(0.018)	(0.826)	(0.035)	(0.017)	(0.018)
Capex	0.012	3.636***	−0.005	0.038*	0.011
	(0.021)	(0.991)	(0.042)	(0.020)	(0.021)
Constant	−0.897***	13.926***	0.299***	−0.795***	−0.873***
	(0.004)	(0.165)	(0.007)	(0.006)	(0.004)
Year	control	control	control	control	control
Industry	control	control	control	control	control
Area	control	control	control	control	control
N	4,144	4,144	4,144	4,144	4,144
R^2	0.548	0.187	0.146	0.600	0.560

Note: Table shows Z-value, with t-value inside parentheses. *, **, and *** indicate a significant level of 10%, 5%, and 1%.

in targeted poverty alleviation is −0.096, indicating that participation in targeted poverty alleviation can significantly reduce financing constraints. Hypothesis 1 has been verified. The results of model b show that the regression coefficients of poverty alleviation investment (Pov) are 1.894 and 0.086, respectively, which the participation of listed companies in targeted poverty alleviation can significantly increase policy resources. Hypothesis 2 is verified. Model c tests the mediation effect. The results show that the regression coefficients of poverty alleviation investment (Pov) are −0.082 and −0.089. The regression coefficient of government subsidies (Sub) is −0.007, and the regression coefficient of tax incentives (Tax) is −0.081, both of which can alleviate financing constraints at the 1% significance level. The absolute value of the coefficient of influence of poverty alleviation investment (Pov) on financing constraints (WW) is reduced from 0.096 to 0.082 and 0.089, indicating that policy resources play an intermediary role in the influence of poverty alleviation investment (Pov) on financing constraints (WW). Hypothesis 3 has been verified.

3.4.3 Robustness tests

Given that there is a two-way causal relationship between poverty alleviation investment and the latter two, that is, the more policy resources, the smaller the financing constraints, and the greater the investment in poverty alleviation. In order to solve this endogenous problem, the explanatory variables are lagging one period instead of the original independent variable for regression.

TABLE 6 One-period lagging regression of independent variables.

Variable	Model a	Model b		Model c	
	WW	Sub	Tax	WW(Sub)	WW(Tax)
Pov	−0.085***	1.652***	0.091***	−0.072***	−0.078***
	(0.006)	(0.233)	(0.010)	(0.005)	(0.006)
Sub				−0.006***	
				(0.000)	
Tax					−0.085***
					(0.010)
Age	−0.001***	−0.002	−0.000	−0.001***	−0.001***
	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)
Top	−0.074***	1.509***	0.054***	−0.066***	−0.070***
	(0.007)	(0.290)	(0.013)	(0.007)	(0.007)
Lev	−0.159***	3.742***	0.015	−0.133***	−0.157***
	(0.006)	(0.267)	(0.012)	(0.006)	(0.006)
Growth	−0.000	−0.112	−0.004	−0.000	−0.001
	(0.003)	(0.116)	(0.005)	(0.003)	(0.003)
CF	−0.076***	−1.422*	0.068*	−0.087***	−0.079***
	(0.019)	(0.801)	(0.036)	(0.018)	(0.019)
Roa	−0.349***	2.775***	0.231***	−0.333***	−0.307***
	(0.023)	(0.971)	(0.044)	(0.022)	(0.023)
Capex	−0.027	3.178***	0.010	−0.003	−0.031
	(0.027)	(1.127)	(0.051)	(0.026)	(0.026)
Constant	−0.905***	14.034***	0.301***	−0.816***	−0.880***
	(0.004)	(0.188)	(0.007)	(0.007)	(0.005)
Year	control	control	control	control	control
Industry	control	control	control	control	control
Area	control	control	control	control	control
N	3,108	3,108	3,108	3,108	3,108
R^2	0.475	0.173	0.115	0.517	0.487

Note: Table shows Z-value, with t-value inside parentheses. *, **, and *** indicate a significant level of 10%, 5%, and 1%.

Due to the limitation of data acquisition, 1 year's data will be reduced compared to the original regression. The specific regression results are shown in Table 6. The regression coefficient of poverty alleviation investment (Pov) in model a is still significantly negative, the regression coefficient of poverty alleviation investment (Pov) in model b is still significantly positive, and the regression coefficients of poverty alleviation investment (Pov) and policy resources in model c are still significantly negative and the absolute value of the regression coefficient of poverty alleviation input (Pov) is smaller than the regression coefficient in model a, which supports Hypotheses 1, 2, and 3.

In addition, an alternative variable method was adopted, replacing the WW index, which measures financing constraints, with the SA index. Since the WW index measures financing constraints, it contains many endogenous variables, such as cash flow, leverage and others, and financing constraints are mutually determined by them. In order to avoid this endogenous influence, Hadlock and Pierce (2010) used the SA index constructed by two exogenous variables of company size (SIZE) and company establishment age (AGE) to measure financing constraints.

The model is as follows:

$$SA_{it} = -0.737^{*}SIZE_{it} + 0.043^{*}SIZE_{it}^{2} - 0.04^{*}AGE_{it} \quad (7)$$

TABLE 7 SA index replaces WW index regression results.

Variable	Model a	Model b		Model c	
	FC	Sub	Tax	FC(Sub)	FC(Tax)
Pov	−0.086***	1.894***	0.086***	−0.080***	−0.073***
	(0.005)	(0.200)	(0.008)	(0.006)	(0.005)
Sub				−0.003***	
				(0.000)	
Tax					−0.152***
					(0.010)
Age	0.004***	0.001	−0.000	0.004***	0.004***
	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)
Top	−0.057***	1.221***	0.039***	−0.053***	−0.051***
	(0.007)	(0.254)	(0.011)	(0.007)	(0.007)
Lev	−0.074***	3.875***	0.024**	−0.061***	−0.070***
	(0.006)	(0.235)	(0.010)	(0.007)	(0.006)
Growth	0.004	−0.058	−0.008*	0.004	0.003
	(0.003)	(0.105)	(0.004)	(0.003)	(0.003)
CF	−0.036*	−1.352*	−0.067**	−0.040**	−0.046**
	(0.019)	(0.709)	(0.030)	(0.019)	(0.019)
Roa	0.016	2.874***	0.520***	0.025	0.095***
	(0.023)	(0.826)	(0.035)	(0.023)	(0.022)
Capex	0.037	3.636***	−0.005	0.050*	0.036
	(0.027)	(0.991)	(0.042)	(0.027)	(0.026)
Constant	1.368***	13.926***	0.299***	1.415***	1.414***
	(0.005)	(0.165)	(0.007)	(0.007)	(0.005)
Year	control	control	control	control	control
Industry	control	control	control	control	control
Area	control	control	control	control	control
N	4,144	4,144	4,144	4,144	4,144
R^2	0.368	0.187	0.146	0.377	0.403

Note: Table shows Z-value, with t-value inside parentheses. *, **, and *** indicate a significant level of 10%, 5%, and 1%.

Since the SA index of the sample companies are all negative numbers, the absolute value of SA is taken as the logarithm to represent the financing constraint FC. The larger the value, the greater the financing constraint. The regression results in Table 7 are basically consistent with the previous regression results, indicating that the results of this study are more reliable.

In addition, the article also selected some sample companies for robustness testing. We selected regions with 100 or more listed companies for study and obtained 3,204 samples in total. The results show that the influence direction and significance of explanatory variables and intermediary variables have not changed. At the same time, we also selected some control variables for the robustness test, and found that the influence direction and significance of explanatory variables and intermediary variables did not change. Further, considering the error terms are correlated among groups, we adopted the "cluster adjustment standard error" (Petersen, 2009). We found that there is also no effect on the significance level of key empirical variables and the mediator variables. Therefore, we believe that the research results are robust.

3.4.4 Further study

In order to reveal the heterogeneity of poverty alleviation among enterprises of different equity natures, the samples were divided into state-owned enterprises and non-state-owned enterprises to perform regression estimation respectively. The results are shown in Tables 8, 9. The results show that the regression results of state-

TABLE 8 State-owned enterprises return results.

Variable	Model a	Model b		Model c	
	WW	Sub	Tax	WW(Sub)	WW(Tax)
Pov	−0.085***	1.297***	0.103***	−0.078***	−0.079***
	(0.006)	(0.286)	(0.013)	(0.005)	(0.006)
Sub				−0.006***	
				(0.000)	
Tax					−0.059***
					(0.009)
Age	−0.000	−0.026**	−0.001*	−0.000	−0.000
	(0.000)	(0.010)	(0.000)	(0.000)	(0.000)
Top	−0.074***	1.123***	0.078***	−0.068***	−0.069***
	(0.008)	(0.408)	(0.018)	(0.008)	(0.008)
Lev	−0.151***	3.890***	0.029	−0.130***	−0.149***
	(0.007)	(0.370)	(0.016)	(0.007)	(0.007)
Growth	−0.025***	−0.056	−0.020***	−0.025***	−0.026***
	(0.003)	(0.162)	(0.007)	(0.003)	(0.003)
CF	−0.109***	−2.769**	−0.128**	−0.124***	−0.116***
	(0.023)	(1.162)	(0.052)	(0.022)	(0.023)
Roa	−0.428***	2.205	0.720***	−0.415***	−0.359***
	(0.033)	(1.167)	(0.075)	(0.031)	(0.033)
Capex	0.015	5.136***	−0.073	0.043	0.011
	(0.033)	(1.169)	(0.075)	(0.032)	(0.033)
Constant	−0.924***	14.514***	0.294***	−0.843***	−0.906***
	(0.007)	(0.342)	(0.015)	(0.009)	(0.007)
Year	control	control	control	control	control
Industry	control	control	control	control	control
Area	control	control	control	control	control
N	2,178	2,178	2,178	2,178	2,178
R^2	0.558	0.220	0.167	0.593	0.566

Note: Table shows Z-value, with t-value inside parentheses. *, **, and *** indicate a significant level of 10%, 5%, and 1%.

owned enterprises and non-state-owned enterprises are basically the same as the above results, in line with Hypotheses 1, 2, and 3. Further performing the Sobel test, the Z value is significant, that is, whether for state-owned enterprises or non-state-owned enterprises, policy resources have an intermediary effect in the relationship between targeted poverty alleviation and financing constraints of listed companies, but the intermediary effects are different. Regarding the policy resource of government subsidies (Sub), the mediation effect of state-owned enterprises accounted for 8.02% of the total effect, and the mediation effect of non-state-owned enterprises accounted for 22.79% of the total effect. The intermediary effect of non-state-owned enterprises is significantly greater than that of state-owned enterprises. In terms of tax incentives (Tax) as a policy resource, the mediation effect of state-owned enterprises accounted for 7.88% of the total effect, and the mediation effect of non-state-owned enterprises accounted for 3.42% of the total effect. The intermediary effect of state-owned enterprises is slightly higher than that of non-state-owned enterprises.

The explanation of this article is that state-owned enterprises have inherent advantages given that state-owned banks can provide guarantees for their financing. The demand for reducing financing constraints by participating in targeted poverty alleviation is lower, so the two intermediary effects are not high. Non-state-owned enterprises are more demanding for more policy resources, and are more likely to obtain more policy resources by participating in targeted poverty alleviation, thereby reducing financing constraints.

TABLE 9 Non-state-owned enterprises return results.

Variable	Model a	Model b		Model c	
	WW	Sub	Tax	WW(Sub)	WW(Tax)
Pov	−0.095***	1.884***	0.032***	−0.060***	−0.092***
	(0.007)	(0.191)	(0.008)	(0.006)	(0.007)
Sub				−0.019**	
				(0.001)	
Tax					−0.092***
					(0.020)
Age	−0.002***	0.026***	0.000	−0.002***	−0.002***
	(0.000)	(0.005)	(0.000)	(0.000)	(0.000)
Top	−0.020**	0.581***	−0.024***	−0.009	−0.022***
	(0.008)	(0.224)	(0.009)	(0.007)	(0.008)
Lev	−0.153***	3.243***	0.008	−0.093***	−0.152***
	(0.007)	(0.198)	(0.008)	(0.006)	(0.007)
Growth	−0.034***	−0.086	0.001	−0.035***	−0.034***
	(0.003)	(0.092)	(0.004)	(0.003)	(0.003)
CF	−0.104***	−0.376	−0.038	−0.097***	−0.107***
	(0.020)	(0.561)	(0.023)	(0.017)	(0.020)
Roa	−0.352***	3.179***	0.408***	−0.293***	−0.315***
	(0.021)	(0.591)	(0.024)	(0.018)	(0.023)
Capex	−0.001	1.478*	0.065**	0.026	0.005
	(0.028)	(0.781)	(0.032)	(0.024)	(0.028)
Constant	−0.897***	14.312***	0.321***	−0.630***	−0.868***
	(0.005)	(0.128)	(0.005)	(0.010)	(0.008)
Year	control	control	control	control	control
Industry	control	control	control	control	control
Area	control	control	control	control	control
N	1966	1966	1966	1966	1966
R^2	0.547	0.330	0.260	0.670	0.552

Note: Table shows Z-value, with t-value inside parentheses. *, **, and *** indicate a significant level of 10%, 5%, and 1%.

However, non-state-owned enterprises have fewer channels to obtain government subsidies as a policy resource, and participation in targeted poverty alleviation is a very important aspect. There are more ways to obtain tax incentives, and it is not necessary to participate in targeted poverty alleviation. Therefore, the intermediary role of tax incentives is significantly less than that of government subsidies.

4 Discussion

First of all, the participation of listed companies in targeted poverty alleviation is a complex work, including nine different poverty alleviation projects or ways. Some previous studies only considered a poverty alleviation project, such as replacing targeted poverty alleviation with industrial targeted poverty alleviation (Yin et al., 2021), while others used the total amount of poverty alleviation investment or the proportion of poverty alleviation investment to assets (Du et al., 2019; Wang and Wang, 2020; Wang et al., 2022). These methods of measuring poverty alleviation investment are not comprehensive enough, especially when the same company participates in different poverty alleviation projects, adding up these poverty alleviation project input implies the equal weight of different poverty alleviation projects. In fact, the weight of different poverty alleviation projects may be different, because different companies attach different importance to and invest in different

poverty alleviation projects. This article uses the grade response models to estimate the difficulty coefficient, which can reflect the differences of various poverty alleviation projects, and then provide more accurate evidence for measuring the potential poverty alleviation input variables.

Secondly, we examined the impact mechanism of participating in targeted poverty alleviation on alleviating corporate financing constraints. The research found that participating in targeted poverty alleviation can significantly reduce corporate financing constraints, which is consistent with other research conclusion (Deng, Tao, and Ji, 2020), because the government's direct preferential policies and state-owned banks have encouraged enterprises to assume policy-oriented social responsibilities for incentive purposes (Yin et al., 2021). From the perspective of impact mechanism, participating in targeted poverty alleviation can help listed companies obtain policy resources, such as government subsidies and tax incentives, which can significantly alleviate the financing constraints of companies. Similarly, Deng, Tao, and Ji (2020) believed that by participating in targeted poverty alleviation, enterprises will receive more economic resources (such as credit support and government subsidies). However, Wang and Wang (2020) found that there is a certain lag in the impact of political connection on the financing constraint mitigation of targeted poverty alleviation.

Finally, policy resources have different impacts on enterprises of different nature. Specifically, the intermediary effect of policy resources on state-owned enterprises to alleviate financing constraints is small. We believe that state-owned listed companies have relatively more policy resources, and participating in targeted poverty alleviation is mainly due to political responsibility and social responsibility. Similarly, Wang and Wang (2020) believe that the mitigation effect of state-owned enterprise financing constraints came from political connection and targeted poverty alleviation. On the other hand, the intermediary effect of government subsidies on non-state-owned listed companies to ease financing constraints is large, while the intermediary effect of tax incentives is small.

5 Conclusion and suggestions

This article reports findings from a study that uses the Shanghai and Shenzhen A-share listed companies participating in targeted poverty alleviation from 2017 to 2020 as a research sample. It makes use of policy resources as an intermediary variable to explore the relationship between listed companies' targeted poverty alleviation investment, policy resources and financing constraints. The study establishes that: 1) The investment in targeted poverty alleviation by listed companies has a significant negative impact on financing constraints, that is, the greater the investment in poverty alleviation, the smaller the financing constraints; 2) The investment in targeted poverty alleviation by listed companies has a significant negative impact on policy resources, that is, the greater the investment in poverty alleviation, the more policy resources they can obtain; 3) Listed companies' investment in targeted poverty alleviation and policy resources have significant negative impact on financing constraints. Policy resources play an intermediary role between poverty alleviation investment and financing constraints. This means that listed companies can increase the policy resources they obtain by participating in targeted poverty alleviation, thereby reducing financing constraints. Further research shows that for enterprises with different equity nature, for instance, in state-owned enterprises; policy resources have a small intermediary role between poverty alleviation inputs and financing constraints. Meanwhile, in non-state-owned enterprises, government subsidies play a significant intermediary role, and tax incentives play a small intermediary role.

Based on the above conclusion, the following suggestions are put forward: First, the regulatory authorities should continuously improve the disclosure system of precise poverty alleviation information. Through institutional constraints, increase the openness and transparency of corporate poverty alleviation information disclosure, so as to give play to the signal transmission function of the securities market. In addition, there is need to provide institutional guarantees for guiding enterprises to participate actively in the governance of relative poverty. Second, the government should strengthen policy incentives to guide enterprises' enthusiasm for participating in targeted poverty alleviation. The implementation of more preferential policies can help attract enterprises, such as broadening the scale of poverty alleviation special debt financing and the scope of green poverty alleviation debt. In order to strengthen government-enterprise cooperation, and promote the solution of problems such as relative poverty in the new stage and achieve the consolidation and expansion of poverty alleviation achievements and the effective connection with rural revitalization. Third, increase the incentives and subsidies for enterprise poverty alleviation development. In particular, increase the subsidy support for private enterprises to participate in poverty alleviation, thereby stimulating the enthusiasm of enterprises to participate in the governance of relative poverty in the new era.

Compared with the existing empirical research on listed companies participating in targeted poverty alleviation to alleviate financing constraints, this article introduces policy resources as an intermediary variable, which not only verifies the direct effect, but also the mechanism of action. However, this article still has some shortcomings. First, the consideration of endogenous problems is not comprehensive enough, and appropriate tool variables to deal with this are not found. Second, our study lacks analysis of the impact of macroeconomic factors. Finally, this article does not take into account the final outcome of poverty alleviation. These areas provide some directions for subsequent research, and future research will improve these deficiencies.

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

ZH: Data curation; Methodology; Project administration; Software; Writing—review and editing. YX: Conceptualization; Data curation; Formal analysis; Project administration; Software; Visualization; Writing—original draft. DL: Formal analysis. MZ: Writing—review and editing; Funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflicts 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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Digitalization, financing constraints and firm performance

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The development of low-level digital technology and communication technology such as "huge wisdom moving cloud" has driven the rise of digital economy, and various fields of social economy have gradually realized deep integration with digital technology. From the micro level of enterprises, digitalization transforms business activities such as research and development, production, supply chain and sales, and forms new data resources to help enterprises achieve lean management through data integration and analysis. To investigate whether digitalization ultimately affects firm performance, this study conducted theoretical discussions, selected Chinese listed companies to study, and empirically tested the relationship. Research has found that digitisation does boost corporate performance. After the robustness test, the conclusion remains the same. To deepen the understanding of the impact of digitalization on corporate performance, a mechanism analysis is also performed in this study. We found that digitization improves corporate performance by improving corporate innovation. In addition, we carried out an applicability analysis. We find that digitalization has a greater impact on firm performance in non-state-owned enterprises and those whose executives have an information technology background. Finally, by means of the economic consequences test, we find that the improvement in corporate performance caused by the growth of the digital hierarchy improves the corporate debt structure in the future. The findings of this study enrich theories related to digitalization and improve empirical evidence for the positive externalities of digitalization.

KEYWORDS

digitalization, financing constraints, enterprise performance, enterprise innovation, economic consequences

1 Introduction

Since the 1990s, the rapid development of the Internet and other digital technologies has brought fresh opportunities for businesses. As micro subjects of economic development, digital transformation of enterprises is the basis for sustainable development of the digital economy (Zhong Yuehua et al., 2022). Enterprises need to actively or passively take full advantage of the opportunities brought by digital technologies to realize business processes (LI et al., 2018), business models (MUBARAK et al., 2020), overseas investment (Hu Yang et al., 2022; Huang and Huang, 2018), financial performance (He Fan, Liu Hongxia, 2019), culture and customer experience (GUENZI et al., 2020) and other aspects of value creation (Wang Haihua et al., 2022). According to the White Paper on Global Digital Economy -- A New Dawn of Recovery under the Impact of COVID-19, released by the China Academy of Information and Communications Technology at the 2021 Global Digital Economy

Conference, the scale of China's digital economy is about 5.4 trillion United States dollars, ranking the second in the world in terms of total volume and the first in terms of year-on-year growth. The digital economy has become a new driving force for China's economic growth.

Digital technology has considerably changed the ecological environment for the survival and development of enterprises, reshaped their business models, and exerted a profound impact on various fields of enterprise operation and management (Li Lei et al., 2022). Through the introduction of digital technology, enterprises have realized the digitalization of production, management and sales at various levels, enhanced their competitiveness, and realized the strategic behavior of short-term and long-term profit increment (Vial, 2019; Verhoef et al., 2021; Hu et al, 2022). The existing literature shows that the impact of digitalization on enterprises is comprehensive and fundamental, and enterprise digitalization is not a choice of whether they are willing or not, but a mandatory task that must be completed (Lu and Lu, 2022). On the one hand, thanks to cloud computing and related auxiliary digital technologies, enterprises can rapidly gather enormous user data at low cost and in multiple dimensions, which improves the immediate response of organizations to market demands (Liu Zheng et al., 2020). On the other hand, digital technology is also a means of organization and management (Goldfarb and Tucker, 2019), which can help enterprises enhance coordination ability and improve supervision efficiency (Brynjolfsson and Mc Elheran, 2016). Digital technology is also a means of organization and management (Goldfarb and Tucker, 2019), which can help enterprises improve coordination ability and supervision efficiency (Brynjolfsson and Mc Elheran, 2016). In recent years, some literature has begun to recognize that corporate digital transformation is not only an application of digital technologies, but also a process of organizational change. That is, the process in which enterprises apply digital technologies such as the Internet of Things, big data and artificial intelligence to process, product and service innovation and promote the restructuring and transformation of enterprise production mode (Lee et al., 2015). Gregory et al. (2019) believe that in this process, enterprises alter the path of value creation through the application of digital technology, so as to improve their internal operating efficiency and organizational performance.

Enterprise performance is an essential indicator to reflect the operating conditions of enterprises in a certain period, and occupies an influential position in the evaluation of enterprise performance (Wang Wenhua et al., 2022). The pursuit of superior performance is a corporate goal. Therefore, it is of practical interest to study the impact of digitalization on corporate performance. The existing literature has made some useful explorations on the relationship between digitization and firm performance. According to some academics, digitalization has done little to improve corporate performance. They believe that when large data is not compatible with the key structure of an organization, digital technology is difficult to create value (Forman and Mc Elheran, 2019), and even causes the "IT efficiency paradox". Another part of scholars believe that IT technology can improve enterprise performance by helping enterprises rationally plan production, quickly respond to consumer demands, and increase organizational flexibility and agility (Mikalefe et al., 2017; Qi Yudong et al., 2020). In addition, digitization can optimize internal and external communication and indirectly improve corporate performance (Alberto et al., 2013). Ferreira et al. (2019), using data from a telephone survey of 938 Portuguese companies, empirically found that the adoption of digital production processes was conducive to the introduction of different products (services). Loebbecke et al. (2015) found that the application of digital technology can influence enterprises to realize innovation transformation behavior under the original R&D innovation, generally improve operational efficiency, reduce operating costs and enhance customer experience, so as to obtain more output performance.

Although several existing studies have explored the relationship between digitization and firm performance, no consensus has been reached. In order to explore the critical factors that drive business performance improvement and provide some insights into the promotion of business digitalization, this study conducted theoretical analysis and empirical tests on the impact of digitalization on business performance. In contrast to existing studies, this study incorporates financing constraints into the research system and analyzes the moderating role of financing constraints in the digital impact on corporate performance. Moreover, based on the existing literature, we also extend the analysis of the specific mechanisms of digitalization affecting the performance of enterprises. Another contribution of this study is an empirical analysis of the economic consequences of digitalization on firm performance.

2 Theoretical analysis and research hypothesis

2.1 Digitalization and enterprise performance

Digitization refers to the process of applying information technology to enterprise production. Digitization can use the current generation of information technology to promote industrial reform, improve the operation efficiency of the industry and build a different economic system (Li Jinyue et al., 2022). With the increasing pressure of resources and environment, the rise of labor costs and the intensification of industry competition, only by further accelerating the construction of digital infrastructure and increasing investment in digital technology can traditional enterprises gain the upper hand in the swift-moving digital trend (Liu Donghui et al., 2022). According to the resource arrangement theory, in the process of digital transformation, enterprises can optimize the allocation of internal resources, improve the productivity of enterprises and improve the performance of enterprises by relying on their own innovation and information acquisition advantages and coordinating various resources (Li Tang et al., 2020). With the development of digitalization, digital transformation has been gradually internalized and integrated into the whole process of daily operation and decision-making of enterprises (GOLDFARB ET AL., 2019). From the perspective of an enterprise, it is clear that the initiatives, capabilities and outcomes of a company's digital transformation will also influence the degree of digitalization of an enterprise and its subsequent performance. Enterprises tend to start from the inside in digital transformation, aiming to improve their efficiency from the inside first (Chi Maomao

et al., 2022), which is bound to be closely related to the promotion of enterprise innovation.

In conclusion, we propose research hypothesis H1:

Hypothesis 1: Digitization helps improve enterprise performance.

Digital transformation integrates scattered information and resources of enterprises, optimizes the connection between supply and demand (LIU et al., 2011), and enables enterprises to achieve higher marginal innovation output (Pan and Gao, 2022). Digital technology of information collection, analysis, processing and feedback is quick, comprehensive, thorough and credible, overflow and low cost, etc., characteristics, guide the enterprises around the key production elements configuration data resources, help to improve enterprise innovation ability, absorption capacity and the ability to adapt, to form a new innovation model (WenHu Hui and sheng-yun wang, 2021) and promoting breakthrough innovation (Jichang Zhang and Jing Long, 2021). Digitalization has changed the traditional pattern of technological innovation in enterprises, bringing convenience advantages to enterprises in information and communication, and enhanced connectivity between enterprises and government departments, scientific research institutions, enterprises in various industries and users. Through this connection, enterprises can pool knowledge from different fields and explore the potential of cross-border innovation (Bai Fuping et al., 2022). The integration of digital technology and production and manufacturing links promotes the formation of an efficient community of people, machines and products in the production process, improves the precision of production process and reduces the difficulty of enterprise process innovation, thus affecting the innovation willingness of enterprises (Zhang Longpeng et al., 2016). When the level of innovation in a business continues to improve, the performance of the business also improves. Technological innovation of enterprises can regularly bring iteration of production process and update of production technology, thus reducing production costs and improving profits of enterprises (Yao Juan et al., 2022). Technological innovation can also help enterprises obtain key resources from social forces for subsequent transformation of technological innovation achievements (Cheng Hong et al., 2016), thus creating competitive advantages for enterprises and improving corporate performance. In addition, large-scale production brought by enterprise innovation enables enterprises to obtain scale effect, which further enables enterprises to obtain certain monopoly profits or excess profits (Duan Haiyan and Tian Yaxing, 2021). As a result, corporate innovation drives corporate performance improvement.

In summary, we believe that enterprise innovation is the intermediary variable of digitalization affecting enterprise performance, so we propose the research hypothesis H2:

Hypothesis 2: Digitization can improve corporate performance by influencing corporate innovation.

2.2 The moderating effect of financing constraints on the relationship between digitalization and corporate performance

Financing constraints are a worldwide problem affecting all aspects of business development. Therefore, it is necessary to incorporate financing constraints into the research regime on the impact of digitalization on corporate performance. The existing literature provides an in-depth analysis of the causes and effects of corporate financing constraints. The financing channels for enterprises mainly include internal financing and external financing. Internal financing is mainly based on an enterprise's own internal surplus, while external financing mainly raises funds from financial institutions, individuals or institutional investors (Du Qianqian and Li Qiqi, 2022). Financing constraints are mainly influenced by factors such as scale and age, political association of enterprises, financial ecological environment, financial development level, relationship between government and market, etc., (Gu Leilei et al., 2018). When times are good, it will be easier for companies to get funding. When enterprises are faced with large financing constraints, they are commonly unable to timely and effectively raise funds for their potential investment projects, so they have to give up some excellent investment opportunities, including mergers and acquisitions (Pan Hongbo et al., 2022; lingling Zhai and Yuhui Wu, 2021; Blouin et al., 2021). Some scholars believe that financing constraints restrict the growth of enterprises, increase the probability of bankruptcy due to the rupture of capital (Musso et al., 2008), and reduce corporate performance and total factor productivity (Hu Xiaoping, 2021; Hua Junguo et al., 2022).

Financing constraints affect not only corporate performance but also corporate innovation. When financing constraints exist, enterprises will reduce the investment of R&D funds, thus inhibiting the improvement of innovation performance (Chen Jingpu and Hu Bo, 2020). Enterprises with severe financing constraints may have R&D projects with broad development prospects, but because of the risk and information asymmetry, the R&D activities of enterprises are stagnant, and the innovation and R&D of enterprises cannot be carried out (Ren Yuxin et al., 2022). As a result, financing constraints, as well as the pressure on the financing environment faced by enterprises, have weakened the boost to business performance from digitalization.

In summary, we believe that financing constraints can play a moderating role in the process of digital impact on enterprise performance, so the research hypothesis H3 is proposed:

Hypothesis 3: When financing constraints are more serious, digitalization plays a smaller role in improving corporate performance.

3 Research design

3.1 Data source and processing

To test the theoretical hypothesis, we use data from 2011 to 2019 for A-share listed companies in mainland China to validate the relationship between digitalization and corporate performance. Given the difficulty of obtaining complete data for non-listed companies, and the advantages of public companies in terms of digitalization and service, as well as transparent data information, public companies were chosen for this study. In addition, given the particularity of financial companies, we also excluded listed companies in the financial sector. According to the following conditions: 1) Remove the samples of ST, *ST and PT; 2)

Remove financial and insurance samples; 3) Eliminate the missing observed values of main research variables; 4) Shrinktail treatment for continuous variables. We end up with 19,021 sample observations. All data was collected from the CSMRA and CNRDS databases and processed using STATA 17.0.

3.2 Model construction

Drawing on previous studies and considering the possible influence of company and year factors on regression results, we construct the following model (1) to test the relationship between digitalization and enterprise performance.

$$roa_{i,t} = \alpha_0 + \alpha_1 \mathrm{dig}_{i,t} + \delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (1)$$

In Formula 1, subscript i is the enterprise and t is the year. The explained variable roa is enterprise performance, the core explanatory variable dig is digitization, and X is control variable. Φ is firm fixed effect, ω is time fixed effect.

In order to test the moderating effect of financing constraints on digitization and firm performance, the cross between dig and SA index (dig*SA) was added on the basis of model (1). The explained variables and control variables were the same as above. The specific model is as follows:

$$roa_{i,t} = \alpha_0 + \alpha_1 dig_{i,t} + \alpha_2 \mathrm{dig} * \mathrm{SA}_{i,t} + \delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (2)$$

3.3 Variable definition

3.3.1 Explained variables

Referring to the research of Wang Wenhua et al. (2022), we use return on total assets (roa) as a measurement index of corporate performance. Because the return on assets can be a comprehensive measure of the enterprise's asset turnover, sales profit rate and equity multiplier. The higher the return on assets, the higher the corporate performance. In addition, earnings per share (pro) is also used for stability test.

3.3.2 Explanatory variables

The importance an enterprise attaches to a particular strategic orientation can frequently be reflected by the frequency of keywords involved in the strategy appearing in the annual report (Wang Hongming et al., 2022). Referring to the existing research, we use Python to crawl and collate the annual reports of Shanghai and Shenzhen A-share listed companies, and extract the keywords of digitization (dig) by Jieba function. On this basis, the 30 words before and after the corresponding keywords are further extracted, and the negative expressions of "no", "no" and additional words before the keywords are eliminated. Finally, the two kinds of word frequency are added together to get the total word frequency (Wu Fei et al., 2021). According to Wang Hongming et al. (2022), considering the obvious right-bias characteristics of such data, this study processed them logarithmically.

3.3.3 Adjusting variables

Following the theoretical analysis, we choose the financing constraint as the regulatory variable. Referring to the research of Ju Xiaosheng et al. (2013), we adopted the SA index as the measurement index of financing constraint (SA). Where, SA = −0.737 × SI + 0.043 × SI2-0.040 × A, SI is the natural logarithm of the total assets of the enterprise, A is the years of listing of the enterprise, SA is negative. Take the absolute value of SA. If the absolute value is larger, the financing constraint is larger.

3.3.4 Intermediary variables

According to the theoretical analysis, we choose enterprise innovation as the intermediary variable. For the measurement of enterprise innovation, we choose the logarithm of total patent application plus 1 to measure enterprise innovation (rd).

3.3.5 Control variables

Drawing on existing literature (Pan Rongrong et al., 2022; Wang Wenhua et al., 2022), To eliminate the influence of heterogeneous factors on enterprise performance, we chose company-level factors such as state, shareholding ratio of the largest shareholder (first), asset-liability ratio (lev), capital intensity (sd), corporate growth, free cash flow (cflo), internal control (con) as the control variables of the model. See Table 1 for a table of variable definitions.

4 Empirical results

4.1 Descriptive statistics

Table 2 lists the descriptive statistical results for the main variables. The mean value and standard deviation of business performance (roa) are 0.0386 and 0.0590. The mean value of digitization (dig) is 1.3230, the maximum value is 5.0690, and the minimum value is 0, indicating that there are great differences in digitization level among Chinese enterprises.

4.2 Regression results

Column 1) in Table 3 shows the regression results of digitalization on enterprise performance. It can be seen that the regression coefficient of digitization (dig) is 0.0015, which is significantly positive at the 1% level. This indicates that digitalization has a positive boost on corporate performance, validating Hypothesis 1. It indicates that in the economic sense, given other variables, the enterprise performance will be 1.0015 times of the original one standard deviation increase in digitization ($e^{0.0015} = 1.0015$). The conclusions of this study are consistent with those of previous studies (Li Yanlong et al., 2022; Wang Wenhua et al., 2022).

Table 3 2) lists the impact of digitalization level on corporate performance after considering financing constraints as a moderating variable. The results show that the coefficient of digitization and financing constraint interaction (dig_sa) is −0.0059, which is significant at the 1% level. This suggests that more severe financing constraints will weaken the boosting effect of digitalization on corporate performance, that is, financing constraints have a negative inhibiting effect on the impact of digitalization on corporate performance, and the research Hypothesis 3 has been validated.

TABLE 1 Variable definition table.

Variable	Symbol	Definition
Corporate performance	roa	Profit/total assets
Digitization	dig	Calculated by the author
Financing constraints	SA	−0.737 × SI + 0.043 × SI2-0.040 × A
Enterprise innovation	rd	ln (Total patent applications + 1)
Duality	state	The value is 1 if the chairman and the general manager are the same. Otherwise, the value is 0
Share proportion of the largest shareholder	first	Largest shareholder shareholding/total shares
Asset-liability ratio	lev	Total liabilities/total assets
Capital-intensity	sd	Operating income/Total assets
Enterprise growth	growth	Revenue growth/Total revenue
Free cash flow	cflo	Cash flow/total assets
Internal controls	con	ln (Internal control index in Dubo database + 1)

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
roa	19,165	0.0386	0.0590	−0.2580	0.1910
dig	19,165	1.3230	1.4170	0	5.0690
state	19,165	0.2680	0.4430	0	1
first	19,165	34.9450	14.9890	8.9300	74.8200
lev	19,165	0.4270	0.2050	0.0520	0.8710
sd	19,165	0.6100	0.4150	0.0760	2.4270
growth	19,165	0.3910	0.9780	−0.6920	6.7569
cflo	19,165	0.0450	0.0690	−0.1590	0.2345
con	19,165	6.4670	1.2520	0	8.4292

4.3 Robustness test

4.3.1 Alternate the explanatory variable

To avoid the instability of the results caused by the digitization level measured by the above method. Referring to the study of Qi Huaijin et al. (2020), we use the natural pair value (cap) of intangible assets at the end of the year to measure the digitalization level of enterprises. The regression results are shown in column (1) of Table 4. The coefficient of cap is 0.0011, which is significantly positive at the 5% level. This still suggests that digitalization can drive improvement in enterprise performance, which is similar to the results of benchmark regression.

4.3.2 Change the explained variable

Based on the study of Wang Wenhua et al. (2022), we choose earnings per share (pro) as an indicator to measure corporate performance to further test robustness. The regression results are shown in column (2) of Table 4. The coefficient of dig is 0.0279, which is significantly positive at the 1% level. It also shows that digitalization drives improved corporate performance. The conclusions of this study remain valid.

4.3.3 Return of GMM

According to the studies of Roodman (2009), Li et al. (2021), Bai and Liu (2018), GMM method can effectively solve the endogeneity problem by constructing equations containing parameters based on moment conditions without assuming the distribution of variables or knowing the distribution information of random disturbance terms. In order to consider the robustness of the results and alleviate the endogenous problems of digitalization, we adopted the system GMM method with higher estimation efficiency for reference to the research of Rao Ping et al. (2022), and took the first-order lag term of digitalization as the instrumental variable of digitalization to conduct the regression again. The regression results are shown in column (3) of Table 4. The coefficient of dig is 0.0018, which is significantly positive at the 10% level. This result is consistent with the research conclusion of Li Yanlong et al. (2022), which also indicates that digitalization promotes the improvement of enterprise performance. The conclusion of this study remain valid.

5 Further discussion

5.1 Mediation effect analysis

Theoretical analysis has shown that increasing the level of digitalization in a business can promote the improvement of its performance. In addition, digitization can improve corporate performance by driving corporate innovation. In the following, we perform an analysis of the mediation effect on this. Digitization plays an vital role in the promotion of enterprise innovation (rd), and can help promote the improvement of enterprise performance. Based on the three-step mediation effect model method of Wen Zhonglin and Ye Baojuan (2014), we established the following model:

$$roa_{i,t} = \alpha_0 + \alpha_1 \mathrm{dig}_{i,t} + \delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (3)$$

TABLE 3 Results of baseline regression.

	(1)	(2)
	Roa	Roa
dig	0.0015***	0.0235***
	(0.0005)	(0.0049)
state	0.0008	0.0022*
	(0.0012)	(0.0012)
first	0.0006***	0.0005***
	(0.0001)	(0.0001)
lev	−0.1307***	−0.1258***
	(0.0034)	(0.0035)
sd	0.0281***	0.0310***
	(0.0018)	(0.0019)
growth	0.0039***	0.0036***
	(0.0004)	(0.0004)
cflo	0.1342***	0.1309***
	(0.0059)	(0.0059)
con	0.0122***	0.0115***
	(0.0003)	(0.0003)
dig_sa		−0.0059***
		(0.0013)
_cons	−0.0311***	−0.0273***
	(0.0034)	(0.0035)
Control	YES	YES
Firm_FE	YES	YES
Year_FE	YES	YES
Obs	19,021	17,508
r2_a	0.5357	0.5313

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

$$rd_{i,t} = \alpha_0 + \alpha_1 \mathrm{dig}_{i,t} + \delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (4)$$

$$roa_{i,t} = \alpha_0 + \alpha_1 \mathrm{dig}_{i,t} + \alpha_2 \mathrm{rd}_{i,t} + \delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (5)$$

Model (3) is the same as model (1).

The above model is regressed and the results are shown in Table 5. In column (2), the coefficient of dig is 0.0982, which is significantly positive at the 1% level. This shows that digitization does drive innovation in businesses. In column (3), the coefficient of dig is 0.0010, but not significant, and the coefficient of rd is 0.0007, which is significantly positive at the 5% level. Since the dig coefficient was not significant, according to the study of Wen Zhonglin and Ye Baojuan (2014), we should conduct additional Bootstrap test at this time to further confirm the establishment of this mediation effect. The test results for Bootstrap are shown in Table 6. We can find that the model passes the Bootstrap test and the mediation effect is significantly established. This suggests that digitization can undoubtedly improve business performance by driving business innovation, and that the research Hypothesis 2 holds.

5.2 Applicability analysis

5.2.1 Whether the difference of enterprise nature changes the impact of digitalization on enterprise performance

Differences in business objectives and risk control between SOEs and non-SOEs will have an impact on corporate activities, which in turn will have an impact on corporate performance. Like most scholars, this study also analyzes the effect of differences in the nature of the firms on the conclusions reached. We conducted regression for samples of state-owned enterprises and samples of

TABLE 4 Robustness test.

	(1)	(2)	(3)
	Roa	Pro	Roa
cap	0.0011**		
	(0.0005)		
dig		0.0279***	0.0018*
		(0.0064)	(0.0010)
L.roa			0.2638***
			(0.0115)
state	0.0015	0.0251	−0.0035*
	(0.0014)	(0.0158)	(0.0019)
first	0.0006***	0.0075***	0.0006***
	(0.0001)	(0.0008)	(0.0001)
lev	−0.1338***	−0.9574***	−0.1794***
	(0.0041)	(0.0459)	(0.0065)
sd	0.0258***	0.2006***	0.0215***
	(0.0022)	(0.0250)	(0.0034)
growth	0.0040***	0.0509***	0.0033***
	(0.0005)	(0.0055)	(0.0006)
cflo	0.1291***	1.3089***	0.0982***
	(0.0069)	(0.0798)	(0.0086)
con	0.0125***	0.1311***	0.0110***
	(0.0003)	(0.0040)	(0.0004)
_cons	−0.0455***	−0.5382***	−0.0106*
	(0.0086)	(0.0457)	(0.0062)
Control	YES	YES	YES
Firm_FE	YES	YES	YES
Year_FE	YES	YES	YES
Obs	14,830	19,021	15,188
r2_a	0.5402	0.6150	

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

non-state-owned enterprises respectively, and the regression results are shown in columns (1) and (2) of Table 7. It can be seen that digitalization has an impact coefficient of 0.0012 on corporate performance in SOEs, which is significantly positive at the level of 10 percent. The coefficient of influence of digitalization on business performance is 0.0017 for non-state-owned enterprises, which is significantly positive at the 1 percent level. This shows that improving the level of digitalization in non-state-owned enterprises can effectively improve the performance of enterprises. Compared with non-state-owned enterprises, state-owned enterprises operate with the goal of promoting the maximization of social and national interests rather than merely their own profits. As a result, SOEs have not taken all of the positive externalities of digitization into their own hands.

5.2.2 Whether the IT background difference of senior executives changes the impact of digitalization on enterprise performance

As the core elements of enterprise operation, senior management is an influential executor who plays the leadership function and achieves the objectives of the board of directors of the enterprise (Hua Weiqing et al., 2015). The heterogeneity of information technology backgrounds of senior executives means that they differ in the basis of their digitalisation perceptions and their ability to identify opportunities for digitalisation, resulting in differences in the impact on corporate performance. For reference to the research of Li Ruijing et al. (2022), we establish the dummy variable of senior executives' information technology background

TABLE 5 Analysis of mediating effect.

	(1)	(2)	(3)
	Roa	rd	Roa
dig	0.0015***	0.0982***	0.0010
	(0.0005)	(0.0241)	(0.0007)
rd			0.0007**
			(0.0004)
state	0.0008	−0.0790	0.0017
	(0.0012)	(0.0586)	(0.0017)
first	0.0006***	−0.0021	0.0006***
	(0.0001)	(0.0033)	(0.0001)
lev	−0.1307***	0.4065**	−0.1130***
	(0.0034)	(0.1850)	(0.0054)
sd	0.0281***	−0.1884*	0.0427***
	(0.0018)	(0.1075)	(0.0031)
growth	0.0039***	0.0436*	0.0054***
	(0.0004)	(0.0259)	(0.0008)
cflo	0.1342***	0.2610	0.1457***
	(0.0059)	(0.3314)	(0.0097)
con	0.0122***	0.0027	0.0125***
	(0.0003)	(0.0170)	(0.0005)
_cons	−0.0311***	3.7408***	−0.0551***
	(0.0034)	(0.1864)	(0.0056)
Control	YES	YES	YES
Firm_FE	YES	YES	YES
Year_FE	YES	YES	YES
Obs	19,021	8,799	8,799
r2_a	0.5357	0.6451	0.5427

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

TABLE 6 Bootstrap test.

Variables	(1)
	y1
_bs_1	0.0001**
	(0.00005)
_bs_2	0.0010***
	(0.00038)
Observations	9,199

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

(Dceo). Dceo has a value of 1 if the executive has an IT background; Otherwise, it is 0. Moreover, we conducted grouping regression according to the information technology background of senior executives, and the regression results are shown in columns (3) and (4) of Table 7. In column (3), the coefficient of dig is 0.0043, which is significantly positive at the 10% level. In column (4), the

TABLE 7 Applicability analysis.

	(1)	(2)	(3)	(4)
	Roa	Roa	Roa	Roa
dig	0.0012*	0.0017***	0.0043*	0.0013***
	(0.0007)	(0.0006)	(0.0024)	(0.0005)
state	0.0012	0.0006	0.0002	0.0010
	(0.0018)	(0.0015)	(0.0053)	(0.0012)
first	0.0002***	0.0007***	0.0012***	0.0005***
	(0.0001)	(0.0001)	(0.0004)	(0.0001)
lev	−0.1273***	−0.1253***	−0.1006***	−0.1329***
	(0.0050)	(0.0046)	(0.0187)	(0.0035)
sd	0.0329***	0.0251***	0.0276***	0.0273***
	(0.0023)	(0.0026)	(0.0093)	(0.0019)
growth	0.0030***	0.0042***	0.0037*	0.0038***
	(0.0005)	(0.0006)	(0.0020)	(0.0004)
cflo	0.1198***	0.1426***	0.1559***	0.1300***
	(0.0076)	(0.0081)	(0.0292)	(0.0060)
con	0.0078***	0.0146***	0.0193***	0.0117***
	(0.0004)	(0.0004)	(0.0016)	(0.0003)
_cons	0.0096**	−0.0533***	−0.1188***	−0.0249***
	(0.0048)	(0.0045)	(0.0187)	(0.0035)
Control	YES	YES	YES	YES
Firm_FE	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES
Obs	7,097	11,912	1,402	17,479
r2_a	0.5992	0.5226	0.5209	0.5454

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

coefficient of dig is 0.0013, which is significantly positive at the 1% level. This suggests that the digitalization of enterprises with information technology background executives can drive the improvement of corporate performance better than that of enterprises without IT background. The information technology background of senior executives can improve the possibility of enterprises applying information technology in operation and management, and improve the application quality of information technology, so as to ensure the better implementation of various control activities and improve the efficiency of internal information communication of enterprises (Li Ruijing et al., 2022), so as to improve corporate performance.

5.3 Analysis of economic consequences

With the continuous improvement of enterprises' digitalization level, the cooperation space of enterprises has been expanded, which makes it easy for enterprises to adopt modern technologies, different business forms and different operation modes, and realize value reconstruction through optimization measures such as penetration, integration and linkage, so as to reduce the financial pressure of enterprises and achieve high-quality development (Zhao Yan, 2022). The high-quality development of enterprises has allowed them to gradually wean themselves off bank loans and gradually improve their debt structures. To test whether the improvement in firm performance due to digitalization improves firms' dependence on bank loans, this study conducted an economic consequence test. We use the ratio of short-term and long-term borrowings to total liabilities (Dbank) to measure the dependence of enterprises on bank loans. Referring to Kim et al. (2021), this economic consequence is identified by estimating the following two-stage model.

$$\Delta roa_{i,t} = \alpha_0 + \alpha_1 \Delta dig_{i,t} + \delta \Delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (6)$$

$$\Delta Dbank_{i,t+1} = \alpha_0 + \alpha_1 \widehat{\Delta roa_{i,t}} + \delta \Delta X + \varphi_i + \omega_t + \varepsilon_{i,t} \quad (7)$$

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TABLE 8 Analysis of economic consequences.

	(1)	(2)
	Δroa	ΔDbank
Δdig	0.0022***	
	(0.0006)	
Δroa		−0.1008*
		(0.0588)
Δstate	−0.0020	
	(0.0016)	
Δfirst	0.0004***	
	(0.0001)	
Δlev	−0.1572***	
	(0.0057)	
Δsd	0.0282***	
	(0.0030)	
Δgrowth	0.0021***	
	(0.0004)	
Δcflo	0.0781***	
	(0.0062)	
Δcon	0.0097***	
	(0.0003)	
Δstate		−0.0022
		(0.0036)
Δfirst		−0.0003*
		(0.0002)
Δlev		−0.2755***
		(0.0118)
Δsd		0.0166***
		(0.0061)
Δgrowth		0.0016
		(0.0012)
Δcflo		0.0224
		(0.0186)
Δcon		0.0026**
		(0.0012)
_cons	−0.0036***	0.1129***
	(0.0004)	(0.0118)
Control	YES	YES
Firm_FE	YES	YES
Year_FE	YES	YES

(Continued on following page)

TABLE 8 (*Continued*) **Analysis of economic consequences.**

	(1)	(2)
	Δroa	ΔDbank
Obs	14,759	8,104
r2_a	0.0864	0.0138

Note: *, ** and *** denote significance at the significance level of 10%, 5%, and 1%, respectively.

Among them, $\widehat{\Delta roa_{i,t}}$ for Δ *roa* fitting values. The regression results are shown in Table 8. In column (1), the coefficient of Δdig is 0.0022, indicating that the change of digitalization positively promotes the change of enterprise performance. In column (2), the coefficient of Δroa is −0.1008, indicating that the change of corporate performance improves the corporate debt structure in the future.

6 Research conclusion and suggestions

6.1 Research conclusion

In the context of the rapid development of the digital economy, the development of enterprises is bound to be affected by digitalization. In this context, this study provides an in-depth analysis of the relationship between digitalization and corporate performance. Building on existing research, we incorporate financing constraints into this research regime and extend the analysis of specific mechanisms of digitalization affecting firm performance. In addition to this, we performed an economic consequences analysis. Research has found that digitization can genuinely improve corporate performance. After the robustness test, the conclusion remains valid. In the subsequent analysis of the mediation effect, we demonstrate the validity of the mediation mechanism in a theoretical analysis. We found that digitization can positively improve corporate performance by driving corporate innovation. In the applicability analysis, we find that the impact of digitalization on firm performance is more pronounced in non-state-owned enterprises and those whose executives have information technology backgrounds. Finally, in the test of economic consequences, we find that improved corporate performance due to higher levels of digitalization improves the corporate debt structure in the future.

6.2 Research limitations and future suggestions

Still, the research is not without its limitations. This article only focuses on the situation in China and lacks empirical analysis of other countries. The specific impact of digitalization on corporate performance calculated in this paper is 0.0015. However, China has a large number of listed companies and the situation of each company is different, so it is difficult for companies to make specific R&D investment plans based on this number. The study lacks additional concrete theoretical justification. In addition, this study does not further explore more mediation mechanisms and heterogeneity in the impact of digitalization on firm performance. If more empirical experience could be provided on the impact of R&D investment on firm performance, it would provide more support for the development of digitalization theory and enable a greater understanding of the positive externalities of digitalization.

In the future, researchers should consider more countries and construct different metrics to measure the level of digitalization of SMES and other hard-to-get data that should be available. Researchers should build a more in-depth theoretical model to demonstrate the impact of digitalization on corporate performance and thus accurately measure the specific magnitude of the impact of digitalization on corporate performance. In the future, researchers should also consider the long-term effects of digitization on firm performance (hu et al., 2022b; Huang and huang, 2018; Lu and Lu, 2022; pan and gao, 2022).

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.

Author contributions

YK: Software, writing—original draft, validation, investigation, data curation, manuscript revision, financial support MF: Methodology, writing—original draft, resources, finalize, supervision, software, manuscript revision YF: Conceptualization, writing—original draft, supervision, finalize, financial support and manuscript revision YJ: Conceptualization, methodology, supervision, financial support and manuscript revision JB: Conceptualization, supervision, software, financial support and manuscript revision.

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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Greenhouse gas emissions and Green Deal in the European Union

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Greenhouse gas emissions (GE) represent an element that influences the lives of all people on the planet. This action must be controlled and prevented because the negative effects are starting to appear more and more in everyday life, sometimes with devastating consequences from a climate point of view and not only for the inhabitants of certain regions. At the European level, one of the main measures taken was the implementation of the Green Deal as a response to the fight against GE. The purpose of this article is to offer a description of the main elements that are influencing the GE, as well as the role of the Green Deal. It also aims to identify the characteristics of the EU countries from the GE point of view before and after the Green Deal was proposed. In this regard two more cluster analyses are also carried out regarding GE at the European level. One analysis concerns the identification and evolution of the main groups of countries from this point of view for years 2018 and 2020. The second analysis concerns the main fields in the industry for year 2020. The used methodology was DM-CRISP. In the final part of the article the obtained results are analyzed, a discussion is added based on them and also a conclusion section.

KEYWORDS

greenhouse emissions, Green Deal, climate change, European Union, cluster analysis

1 Introduction

One of the most important elements that influence the environment and affect life on the entire planet is represented by greenhouse gas emissions (GE). These represent the cumulative effect of all the gases emitted into the atmosphere and which have the property of absorbing infrared radiation emitted from the surface of Earth and reradiating it back to the Earth's surface (Mann, 2022). According to the same source, the most representative gases that contribute to the creation of GE are carbon dioxide (CO_2), water vapors, and methane (CH_4). Among the greenhouse gas emissions, the carbon dioxide is the most significant element regarding the impact that it has over the environment. It is emitted into the atmosphere both due to natural causes (egg. Volcanic eruptions, decomposition of organic matter, respiration of living organisms, *etc.*) but also due to human activity (burn the fossil fuels, food processing, raise animals, transport, setting a comfortable temperature in buildings, obtaining electricity, burn the forests to create agricultural land and for homes, *etc.*). According to the same source, the carbon dioxide

accumulated in the atmosphere with an average rate of 1.4 part per million (ppm) by volume between 1959 and 2006 and with 2.0 ppm between 2006 and 2018.

Methane is the second most important gas that is emitted, being stronger than the carbon dioxide. The main human activities that emit methane are oil production and transportation, natural gas and coal, agriculture activities, as well as the decomposition of organic matter. Several papers have analyzed this gas and its cycle in nature in order to reduce Methane emissions in the atmosphere (Etminan et al., 2016; Rosentreter et al., 2021; Cadieux et al., 2022).

Some other greenhouse gases that also absorb infrared radiation are nitrous oxides (N_2O) and fluorinated gases (F-gases). In papers like Nisbet et al. (2022) and Zenone et al. (2021) is analyzed the behavior of these gases. Throughout the earth's existence, GHs concentrations have varied greatly, leading to significant climate variations over long periods of time. Based on studies conducted over the time like Nyserda-1 (2021), Nyserda-2 (2021), Nyserda-3 (2019) and IPCC (2014), which were based on data sets that covered long periods of time, it was found that the level of GE concentrations becomes higher in warm periods, having at the same time a tendency to decrease in periods when the temperature is lower.

In the European Union for the year 2019, the distribution of greenhouse gas emissions was (EU-P1, 2021): 80% carbon dioxide, 11% methane, 6% nitrous oxide (N_2O) and 2% hydro-fluorocarbons (HFCs) and around 1% was represented by fluorocarbons (PFCs), mix of PFCs and HFCs, sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). The greenhouse gas emissions in the EU for year 2019 based on economic sectors was as follows (EU-P1, 2021): 77.01% energy, 9.1% industrial processes and product use, 10.55% agriculture, 3.32% waste management. Based on these data, it can be seen that the energy sector is by far the most important source in relation to the others.

Negative effects of the greenhouse gas emissions continue to appear and to influence the lives of people from all over the world. One of the main effects is the climate that is changing inducing not only a rise of the average temperatures (global warming) but also creating extreme weather events, rising seas, shifting wildlife habitats and populations, affecting forests and coastal areas, *etc.* (Mogos et al., 2021; Nunez, 2022). Countries from all over the world acknowledged these facts and tried to accomplish an agreement through the Paris Climate Agreement in 2015. Because of these negative effects that must be reduced, the economies must change, especially for the biggest emitters like China, United States of America, India, and Russia.

In order to combat the negative effects of the greenhouse gas emissions, governments of many countries from all over the world have tried to take several measures through their strategies, policies and by implementing specific programs. For example, in the European Union, among other actions, one big step was the initiative called Green Deal (EU-P2, 2022). In the next section it is analyzed the Green Deal and its role in the European Union fight against the greenhouse gas emissions.

In the United States of America, for example, Environmental Protection Agency had several initiatives regarding strategies and programs regarding the energy efficiency, supply chain, increasing fuel efficiency in logistics and transportation, reducing methane emissions, waste reduction, identifying renewable energy sources and additional resources (EPA-USA, 2022). Papers like Kayakus (2022), Acheampong and Boateng (2019), Kadam and Vijayumar (2018) and Liang et al. (2021) propose the use of artificial intelligence in order to improve certain processes and methods for decreasing the greenhouse gas emissions.

The objectives of the paper are to describe the Green Deal Strategy and to find the answers to four research questions, namely: **1)** which are the main groups (clusters) of countries in the European Union for the years 2018 and 2020 in terms of total greenhouse gas emissions, Carbon dioxide, Methane, Fluorinated gases (F-gases), Nitrous oxides? **2)** which is the dynamics of the groups (clusters) identified in the previous question (point a) for the years 2018 and 2020? In this regard, the analysis identifies the countries that were in a certain group before the initiation of Green Deal strategy and managed to move to another group with different characteristics after 1 year in which there were applied measures proposed by the Green Deal; **3)** which are the characteristics of the profiles for the identified groups for the year 2020 from the point of view of the types of gas emissions ? **4)** which are the most similar sectors of the economy in terms of carbon emissions (CO_2) in 2020 and what are the correlations between them?

The innovative aspect of the paper is the use of the data mining algorithms in identifying groups of EU countries with similar behavior regarding the GE before and after applying the Green Deal recommendations. Also an analysis for the economy sectors based on GE was carried out using also data mining technics.

2 Green Deal and the European Union

The climate is changing especially due to the greenhouse gas emissions and their negative effects that they have on the environment. GEs are affecting both the population and the environment in Europe and in the whole world. Considering this aspect and trying to face the challenges that appear more and more often, the European Commission has proposed the Green Deal strategy in December 2019.

This strategy has the general purpose of improving the wellbeing of people by achieving a climate-neutral and by protecting the natural habitat. Within this strategy, the main objectives consist of: protecting and improving the lives of people and animals by reducing the degree of pollution, obtaining a climate-neutral until the year 2050, offering support to companies to become leaders in obtaining clean products and technology, and also to ensure a transition as fair as possible in which all aspects and all actors involved are taken into account (EC1, 2019). The same document also mentions the following statistical data regarding the perception of Europeans regarding climate change: 93% of them see climate change as a serious problem that must be combated as quickly and efficiently as possible, 93% have taken at least one action to combat climate change and 79% believe that by combating climate change the degree of innovation in many fields will improve.

Considering the proposed objectives, the actions undertaken must take place in almost all areas of the economy within each country in the European Union. Within the strategy, the following actions are recommended (EC1-European Commission, 2019).

TABLE 1 Targets to fulfill EU's commitments under the Paris Agreement. Data source (EC3, 2020).

Targets to fulfill EU's commitments under the paris agreement (year 2015)	Year
	2030 agreed targets
Reduction in greenhouse gas emissions compared to 1990 levels	40%
Renewables in energy mix	32%
Energy efficiency improvement	32,5%
Cars (compared to emissions measured in 2021 starting points)	37,5%
Vans (compared to emissions measured in 2021 starting points)	31%
Lorries, heavy and long vehicles (compared to EU average in the References period (1 July 2019–30 June 2020))	30%

- Decarbonize the energy sector because the production and use of energy produce more than 75% of the EU's greenhouse gas emissions. Papers such as Chioran and Valean (2021) and Ma et al. (2018) propose solutions for this action.
- Construction of energy-wise intelligent buildings as well as the renovation of existing buildings. This measure is indicated to reduce heat losses and, implicitly, to reduce energy bills and the amount of energy used. It is known that 40% of the energy consumed is used for buildings. Papers like Ligardo-Herrera et al. (2022) and Bilardo et al. (2021) propose solutions for this action.
- Offering support to the industry so that an increasing number of companies become leaders in the green economy. According to the statistics, European Industry uses only 12% of recyclable materials.
- Mobility and the need for transport to be satisfied as much as possible using cheaper, cleaner and healthier ways both from the point of view of private transport and public transport. In terms of emissions, transport activities represent 25%. Papers like Bao et al. (2022) and Cui et al. (2020) support this action.

Other important actions that are taken into account to offer European citizens an improved wellbeing are (EC2-European Commission, 2019; Ponce, 2022; McDougall, 2021; Borbujo et al., 2021): cleaning the air, water and soil; packaging reusing and recycling; reducing food waste; creating premises for the use of green energy; renovation and rehabilitation of buildings of major interest and not only such as residential buildings, schools, hospitals, state institutions, *etc.*,; increasing the number of eco-friendly products sold in traditional and online stores; creating the premises for maintaining and improving the health of citizens as well as for the following generations; improving public transport and creating alternatives that use electricity; building an infrastructure for easier charging of electric means of transport; healthier food, obtained by using a smaller amount of pesticides and fertilisers.

In EC3-European Commission (2020) there are facts that are showing that some measures taken in the past during the last couple of years are producing positive effects. For example, between 1990 and 2018, greenhouse gas emissions have decreased by 23%. Meanwhile, the EU economy (EU GDP) has increased by 61%. In this regard, an example of action that was done was the introduction of the energy label for the electrical products, action that has encouraged the consumers to buy products which are more energy efficient.

Some notable values regarding the total greenhouse gas emissions (CO_2e) for EU countries, during the year 2019 are (values are expressed in CO_2 kilotons equivalent (CO_2e (ktn)), meaning the equivalent of emitted gases in CO_2 expressed in kilotones) (EU-P1, 2021): Germany–809,799 CO_2 ktn, France–442,985 CO_2 ktn, Italy–418,281 CO_2 ktn, Poland–390,745 CO_2 ktn, Spain–314,529 CO_2 ktn. Taking into account all the countries from EU, during the year 2019, it was a total amount of greenhouse gas emissions equal to 4,065,462 CO_2 ktn. In comparison with year 2015, in the EU, the total amount of greenhouse gas emitters was equal to 4,499,851 CO_2 kilotons. In the world, also in 2015, some other important greenhouse gas emitters (in CO_2e (ktn)) were (EU-P1, 2021): China–1,306,769 CO_2 ktn, United States–6,444,394 CO_2 ktn, India–3,346,954 CO_2 ktn, Russia–2,233,876 CO_2 ktn, Japan–1,359,553 CO_2 ktn.

Until year 2030, several target aim to be accomplished. Some of these targets are mentioned in Table 1 (EC3, 2020) and are about greenhouse gas emissions, renewable energies, energy efficiency, cut the CO_2 emissions. The last three lines in this table represent the percent that must be achieved in order to reduce the CO_2 emissions in EU until 2030 according to the Paris Agreement regarding the cars, vans, lorries and heavy and long vehicles.

In order to sustain the process needed to accomplish the targets, a transition mechanism is required. According to EC4 (2020), this mechanism will primarily involve helping the sectors of the economy that suffer the most following the transition to the green economy. Elements such as disadvantaged regions, industrial areas and employees who will face the greatest challenges following this transition, will receive special support. In total, at least 100 Billion Euros will be allocated for this transition. They will consist of.

- Financial support: at least 30–50 billion Euros for investment, InvestEU "Just Transition" scheme, allocating 45 billion Euros of investments, a new public sector loan facility allocating around 25–30 Billion Euros, the implementation of transition plans for the regions that will need more in order to direct investments, create attractive conditions and risk sharing for public and private investors, create a platform through which ensures technical assistance for the implementation of the transition mechanism;
- Helping the people who are most vulnerable to the transition: create new opportunities for employment, the unemployment

being a very important problem for EU (Daugeliene and Junevicius, 2021; Mogos et al., 2022). It will offer also the opportunity to the citizens to re-skill themself in different new required work areas, investments will be made in order to increase the energetic efficiency of the buildings, facilities will be created in order to access easier the green energy, the health of the citizens remains one of the most important issues that will be treated with maximum responsibility (Trajkova et al., 2021; Belostecinic, 2022);

- Helping companies and sectors of the economy that work in areas where the amount of carbon emissions is very high: support will be provided for the transition to the use of low-carbon technologies and economic diversification based on climate-resilient investments and jobs; making investments regarding research and innovation activities, the creation of companies and SMEs; facilitating loans and financial support; creating attractive conditions for public and private investors;
- Providing additional aid to member states of the European Union and regions that have a high degree of dependence on fossil fuel and carbon. For these, additional support will be provided for the transition to low-carbon and climate-resilient, the creation of new jobs within the green economy, the provision of technical assistance, the improvement of energy infrastructure and transportation networks, the provision of affordable loans to local public authorities, the realization of investments in renewable energy sources, increasing the degree of digitization and interconnection between the systems and platforms used.

Environmental degradation and climate change undoubtedly affect all people on earth. For this reason, the fight to save the environment through the proposed measures must be carried out at a global level. In this regard, the European Union wants to set an example by implementing the Green Deal strategy, thus becoming a leader to follow. Also, through diplomacy and the development of cooperation, the EU wants to help implement the proposed and implemented measures on a larger scale, helping in this way the other Unions and countries around the world. Actions in this sense are (EC5, 2019): close collaboration with countries on the African continent; the establishment of the Green Agenda following the summit in Poznan (2019), which has the role of being a strategy similar to the Green Deal from the European Union (EC6, 2019); creating partnerships with the Southern and Eastern Neighborhood; establishing collaborative relationships of the Green Alliance type with partners from areas such as Latin America, Asia, the Pacific and the Caribbean; achieving a close collaboration within the G20 with countries that are responsible for 80% of global greenhouse gas emissions.

Regarding the G20, these represent a strategic multilateral platform that has the role of connecting the world's most developed economies. One of its strategic roles is to ensure in securing future global economic growth and prosperity. G20 member countries globally represent more than 80% of world GDP, 75% of international trade and around 60% of the world population (G20, 2021). The G20 members are: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, the United States, and the European Union. Spain is considered a permanent invited guest.

From a financial point of view, on a global level, it could be mentioned that the European Union, through the Green Deal strategy, aims to support around 25% of the expenses of the EU neighbors in terms of implementing development and cooperation tool in order to combat climate change. It should also be mentioned that more than 40% of the global expenses used to combat climate change are provided by the European Union.

3 Research methodology and data

In this section, an analysis of greenhouse gas emissions at the European Union level is carried out. The data used were sent by the European Union countries to the United Nations Framework Convention on Climate Change (UNFCCC) and to the EU Greenhouse Gas Monitoring Mechanism (EU Member States) (EEA, 2022). The platform from which the data were extracted offers the possibility to analyze greenhouse gas emissions at a general level, at the level of economic sectors, at the level of countries, at the level of gas types (Carbon dioxide - CO_2, Methane - CH_4, Fluorinated gases - F-gases (hydro-fluorocarbons (HFCs)), Nitrous oxides - N_2O). The values are expressed in CO_2e (ktn). Within the platform, the time interval for which values are entered is between 1990 and 2020. This long period allows various types of analyses.

In Table 2, the data for the total greenhouse gas emissions at the European Union level were extracted to highlight the differences that appeared 1 year after the start of the proposal of the Green Deal strategy in Europe. The year 2018 (before the initiation of the Green Deal strategy) and 2020 (1 year after the initiation of the Green Deal strategy) were selected. It must to be mentioned that in 2020 only a small part of the initial proposals within the strategy were adopted and their implementation began. However, many countries tried to take into account the guidance offered by the Green Deal strategy.

Based on the comparison between the 2 years, it can be observed that 25 countries out of 27 had a total of lower greenhouse gas emissions in 2020 compared to 2018, a fact that confirms the effectiveness of the measures taken within the Green Deal strategy even after only 1 year. Only two countries, namely, Latvia and Lithuania, have had an increase between 2018 and 2020 in greenhouse gas emissions (the result in the third column of Table 2 being negative). In Figure 1 it can be seen the differences between the countries of the European Union as well as the total level of greenhouse gas emissions in 2018 and 2020. From this point of view, the most important countries are Germany, France, Italy, Poland and Spain.

In order to have an overview regarding the CO_2e (ktn) on a long time period, data were selected between 2010 and 2020. Based on these data, it can be observed that during this 12 years, there were only few years (like 2013 and 2017) when the CO_2e (ktn) had a pronounced decreased.

In general, regarding this time period, the CO_2e (ktn) remained the same. A major decrease it could be seen starting with 2019 (Figure 2).

TABLE 2 EU27 - All greenhouse gases - (CO_2e (ktn)) in 2018 and 2020. Data source: (EEA, 2022).

Country	All greenhouse gases–(CO_2e (ktn)) in 2018	All greenhouse gases–(CO_2e (ktn)) in 2020	Differences between 2018 and 2020
Austria	77.971	73.392	4.579
Belgium	122.187	109.735	12.452
Bulgaria	51.036	40.001	11.035
Croatia	19.741	18.616	1.126
Cyprus	9.562	8.859	703
Czech Rep	132.100	126.462	5.637
Denmark	55.224	45.839	9.384
Estonia	18.898	12.926	5.972
Finland	51.194	31.355	19.838
France	447.514	387.069	60.446
Germany	860.653	731.226	129.427
Greece	92.178	72.217	19.960
Hungary	61.163	56.307	4.857
Ireland	72.509	65.830	6.679
Italy	406.158	352.667	53.491
Latvia	11.142	11.286	−144
Lithuania	14.187	14.939	−752
Luxembourg	12.277	10.378	1.899
Malta	2.512	2.319	193
Netherlands	201.965	174.554	27.411
Poland	377.413	356.423	20.991
Portugal	64.685	52.372	12.312
Romania	88.297	77.184	11.114
Slovakia	36.110	28.357	7.753
Slovenia	18.719	11.142	7.577
Spain	313.597	245.671	67.926
Sweden	20.461	7.461	13.000

Next, a clustering type data mining analysis is carried out, which aims to answer to the research questions, namely,

a) For the first question to identify the main groups (clusters) of countries from the EU for years 2018 and 2020 in terms of total greenhouse gas emissions, Carbon dioxide, Methane, Fluorinated gases (F-gases), Nitrous oxides;
b) For the second question to identify the dynamics of the groups (clusters) identified in the previous question (point a) for the years 2018 and 2020? For this case, the analysis took into account the Green Deal Strategy and identifies the countries that were in a certain group before the initiation of it and then moved into another group with different characteristics after 1 year in which there were applied measures proposed by it;
c) For the third question to find out the characteristics of the profiles for the identified groups for the year 2020 from the point of view of the types of gas emissions?
d) For the fourth question to identify the most similar sectors of the economy in terms of carbon emissions (CO_2) for year 2020 and which are the correlations between them?

In the data analysis, the *CRoss Industry Standard Process for Data Mining* (DM-CRISP) methodology was used, a specific methodology for data mining analysis (CRISP-DM, 2022; RRID: SCR_019811). This methodology consists of the following stages, each stage with specific question(s) (Hotz, 2023): requirements understanding (What does the activity/business/project need?), data understanding (What data do we have/need? They are clean

FIGURE 1
EU27 - CO_2e (ktn) in 2018 and 2020. Data source: (EEA, 2022).

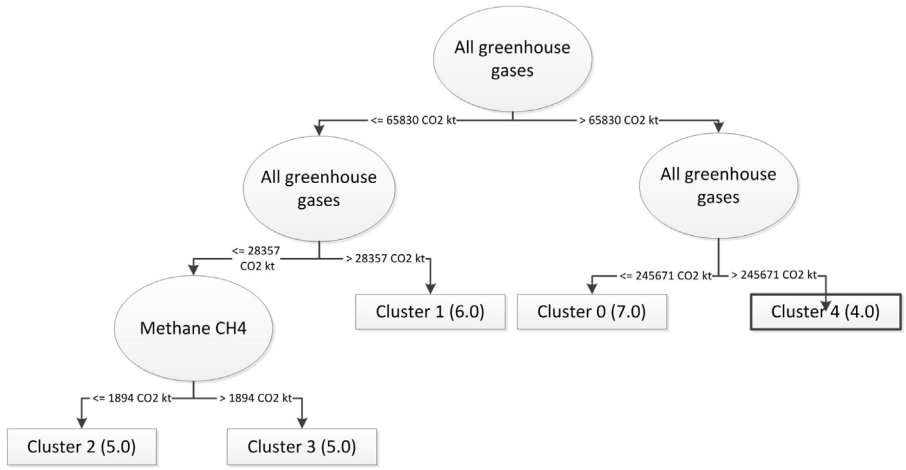

FIGURE 2
Eu countries–CO_2e (ktn) between 2010 and 2020.

enough?), data preparation (In order to model the data, how do we organize it first?), data modeling (Should I apply some specific modeling techniques?), evaluation (According to the activity/business/project objectives and goals, which model fits better?), and deployment (How the results and their interpretations could be accessed by the beneficiaries?).

A cluster analysis type is about grouping a set of instances (or objects) in a certain way in which the instances distributed in the same

group (called a cluster) are more similar (based on the analyzed attributes) to each other than to those in other groups (clusters).

The software that was used to process the data and to run the algorithm is Weka (2022). The algorithm used for cluster identification is Simple K-Means and for rule identification the Nearest-neighbor-like algorithm (NNge) (RRID:SCR_016719).

The Simple K-Means algorithm has several steps as follows: 1) the number of clusters K if selected (it may be identified using algorithms like EM), 2) then select random K centroids (or points), 3) after this assign each data point to their closest centroid based on a computed distance (distances like Euclidian distance, Manhattan distance, Chebyshev distance, *etc.*) which will form the predefined K clusters, 4) then the variance is computed and place a new centroid of each cluster. The steps 1), 2) and 3) repeat, this means to reassign each data point into a new closest centroid of each cluster. In the situation in which reassignments occur then the step 4) is done again. Otherwise the algorithm stops.

4 Results

In the current section, data analyses are carried out in order to find the answer to the research questions mentioned above. In the first part (4.1) the authors try to find out the answer to the first three questions and in the second part (4.2) the answer for the last question.

4.1 Cluster analysis based on greenhouse gas emissions for the countries from European Union

This section aims to answer to the first three research questions from those mentioned above. The cluster analysis for EU27 countries regarding the greenhouse gas emissions is carried out for the years 2018 and 2020, values being expressed in CO_2e (ktn). The time period selected was the year 2018 being the moment before the initiation of the Greed Deal and the year 2020 being the moment when the first Green Deal initiative began to be adopted and has offered recommendations for different aspects of the economy.

The algorithm used to carry out the clustering process is Simple K-Means, and the values for the parameters used were: Euclidean distance (the computed distance that is used to see how different or similar are two instances), the maximum number of iteration was set to 500 (how many times the algorithm to be applied based on the new obtained data), the cluster number after several tries was set to 5 (the number of groups which is an input parameter for the used algorithm), the number of seed (the random number seed to be used) was set to 10, the option to preserve the instance order was set to false.

For the cluster analyses for the years 2018 and 2020, the groups (clusters) of countries that are similar in terms of greenhouse gas emissions were obtained, taking into account their total values as well as each type of gas separately, respectively methane, carbon dioxide, fluorinated gases and nitrous oxides. The values mentioned for each group represent the most representative values for the group, so that the countries assigned to that group have values close to those values. In computing these values, according to the Simple K-Means algorithm, all values, from all types of gas and total values, were taken into account.

For the year 2018, according to the clustering process, the following results were obtained (the values are expressed in CO_2e (ktn)):

Cluster 0: all greenhouse gas emissions are around 90,026.1667 CO_2 ktn, Methane (CH_4) is around 8,548.3333 CO_2 ktn, Carbon dioxide (CO_2) is around 72,324.8333 CO_2 ktn, Fluorinated gases are around 4,400.3333 CO_2 ktn, Nitrous oxides (N_2O) is around 4,752.6667 CO_2 ktn. Six countries were distributed in this cluster, namely: Austria, Belgium, Bulgaria, Czech Republic, Greece, and Portugal. The most representative country for this cluster is Austria.

Cluster 1: all greenhouse gas emissions are around 104,498.75 CO_2 ktn, Methane (CH_4) is around 15,909.5 CO_2 ktn, Carbon dioxide (CO_2) is around 15,909.5 CO_2 ktn, Fluorinated gases are around 1,263.25 CO_2 ktn, Nitrous oxides (N_2O) is around 8,429.25 CO_2 ktn. Four countries were distributed in this cluster, namely: Denmark, Ireland, Netherlands, and Romania. The most representative country for this cluster is Denmark.

Cluster 2: all greenhouse gas emissions are around 12,185 CO_2 ktn, Methane (CH_4) is around 1,220.1667 CO_2 ktn, Carbon dioxide (CO_2) is around 9,941.8333 CO_2 ktn, Fluorinated gases is around 255 CO_2 ktn, Nitrous oxides (N_2O) is around 768.3333 CO_2 ktn. Six countries were distributed in this cluster, namely: Cyprus, Estonia, Latvia, Luxembourg, Malta, and Slovenia. The most representative country for this cluster is Cyprus.

Cluster 3: all greenhouse gas emissions are around 33,809.3333 CO_2 ktn, Methane (CH_4) is around 4739 CO_2 ktn, Carbon dioxide (CO_2) is around 23,838.5 CO_2 ktn, Fluorinated gases are around 1,182.3333 CO_2 ktn, Nitrous oxides (N_2O) is around 4,049.8333 CO_2 ktn. Six countries were distributed in this cluster, namely: Croatia, Finland, Hungary, Lithuania, Slovakia, and Sweden. The most representative country for this cluster is Croatia.

Cluster 4: all greenhouse gas emissions are around 481,067 CO_2 ktn, Methane (CH_4) is around 48,008.4 CO_2 ktn, Carbon dioxide (CO_2) is around 393,534.8 CO_2 ktn, Fluorinated gases are around 12,287.8 CO_2 ktn, Nitrous oxides (N_2O) is around 27,236.2 CO_2 ktn. Five countries were distributed in this cluster, namely: France, Germany, Italy, Poland, and Spain. The most representative country for this cluster is France.

These results are summarized in Table 3. In this table, the values are expressed in CO_2e (ktn).

For the year 2020, following the clustering process, the following results were obtained (the values are expressed in CO_2e (ktn)); Cluster *0:* all greenhouse gas emissions is around 125,602.1429 CO_2 ktn, Methane (CH_4) is around 15,972.4286 CO_2 ktn, Carbon dioxide (CO_2) is around 98,161 CO_2 ktn, Fluorinated gases are around 3,433.5714 CO_2 ktn, Nitrous oxides (N_2O) is around 8,035.2857 CO_2 ktn. Seven countries were distributed in this cluster, namely: Austria, Belgium, Czech Republic, Greece, Netherlands, Romania, and Spain. The most representative country for this cluster is Austria.

Cluster 1: all greenhouse gas emissions is around 48,617.3333 CO_2 ktn, Methane (CH_4) is around 8,517.6667 CO_2 ktn, Carbon dioxide (CO_2) is around 32,903.3333 CO_2 ktn, Fluorinated gases are around 1,594.3333 CO_2 ktn, Nitrous oxides (N_2O) is around 5,602.3333 CO_2 ktn. Six countries were distributed in this cluster, namely: Bulgaria, Denmark, Finland, Hungary, Ireland, and Portugal. The most representative country for this cluster is Bulgaria.

TABLE 3 Cluster analysis results for year 2018 for EU27 (values in CO_2e (ktn)).

Attribute	Cluster 0	Cluster 1	Cluster 2	Cluster 3	Cluster 4
	6 (22%)	4 (15%)	6 (22%)	6 (22%)	5 (19%)
Country	Austria	Denmark	Cyprus	Croatia	France
All greenhouse gases	90,026.1	104,498.7	12,185	33,809.3	481,067
Methane (CH_4)	8,548.3	15,909.5	1,220.1	4,739	48,008.4
Carbon dioxide (CO_2)	72,324.8	78,896	9,941.8	23,838.5	393,534.8
Fluorinated gases	4,400.3	1,263.2	255	1,182.33	12,287.8
Nitrous oxides (N_2O)	4,752.6	8,429.2	768.3	4,049.8	27,236.2
Clusters	Cluster 0	Cluster 1	Cluster 2	Cluster 3	Cluster 4

TABLE 4 Cluster analysis results for year 2020 for EU27 (values in CO_2e (ktn)).

Attribute	Cluster 0	Cluster 1	Cluster 2	Cluster 3	Cluster 4
	7 (25%)	6 (22%)	5 (19%)	5 (19%)	4 (15%)
Country	Austria	Bulgaria	Cyprus	Croatia	France
All greenhouse gases	125,602.1	48,617.3	9,124.8	16,131.8	456,846.2
Methane (CH4)	15,972.4	8,517.6	960	3,354.4	48,514
Carbon dioxide (CO_2)	98,161	32,903.3	7,380.6	8,911.4	368,183.2
Fluorinated gases	3,433.5	1,594.3	244.8	842.6	11,708
Nitrous oxides (N_2O)	8,035.2	5,602.3	539.8	3,023.6	28,440.7
Clusters	Cluster 0	Cluster 1	Cluster 2	Cluster 3	Cluster 4

Cluster 2: all greenhouse gas emissions is around 9,124.8 CO_2 ktn, Methane (CH_4) is around 960 CO_2 ktn, Carbon dioxide (CO_2) is around 7,380.6 CO_2 ktn, Fluorinated gases are around 244.8 CO_2 ktn, Nitrous oxides (N_2O) is around 539.8 CO_2 ktn. Six countries were distributed in this cluster, namely: Cyprus, Estonia, Luxembourg, Malta, and Slovenia. The most representative country for this cluster is Cyprus.

Cluster 3: all greenhouse gas emissions is around 16,131.8 CO_2 ktn, Methane (CH_4) is around 3,354.4 CO_2 ktn, Carbon dioxide (CO_2) is around 8,911.4 CO_2 ktn, Fluorinated gases are around 842.6 CO_2 ktn, Nitrous oxides (N_2O) is around 3,023.6 CO_2 ktn. Five countries were distributed in this cluster, namely: Croatia, Latvia, Lithuania, Slovakia, and Sweden. The most representative country for this cluster is Croatia.

Cluster 4: all greenhouse gas emissions is around 456,846.25 CO_2 ktn, Methane (CH_4) is around 48,514 CO_2 ktn, Carbon dioxide (CO_2) is around 368,183.25 CO_2 ktn, Fluorinated gases are around 11,708 CO_2 ktn, Nitrous oxides (N_2O) is around 28,440.75 CO_2 ktn. Four countries were distributed in this cluster, namely: France, Germany, Italy, and Poland. The most representative country for this cluster is France.

These results are summarized in Table 4. In this table, the values are expressed in CO_2e (ktn).

In Figures 3, 4 there are presented maps for years 2018 and 2020 regarding the countries, the CO_2e (ktn) and the cluster assignment.

Analyzing values from 2018 in relation to those from 2020, it can be observed that for the most countries the values are lower. An important factor, in addition to the initiatives taken within the Green Deal strategy, was also the emergence of the COVID-19 pandemic, which blocked the countries' economies to a large extent and has decreased the greenhouse gas emissions (Le Quere et al., 2020; Kumar et al., 2022). However, based on the mining analysis carried out, some countries were distributed in 2018 in certain clusters and in 2020 in other clusters; this means that, in relation to the general trend, they presented significant differences. Based on the clusters results of the years 2018 and 2020 it can be observed that several countries have made sustained efforts to reduce their level of greenhouse gas emissions, but others have not managed to reduce as much as they wanted total greenhouse gas emissions. The countries that have presented big differences compared to the majority are (Table 5): Bulgaria (in 2018 it was in Cluster 0 with an average of approx. 90,026 CO_2 ktn per total emissions and for 2020 it moved to Cluster 1 which has an average of 48,617 CO_2 ktn), Finland (in 2018 it was in Cluster 3 with an average of approx. 33,809 CO_2 ktn per total emissions and for 2020 it moved to Cluster 1 which has an average of 48,617 CO_2 ktn), Hungary (in 2018 it was in Cluster 3 with an average of approx. 33,809 CO_2

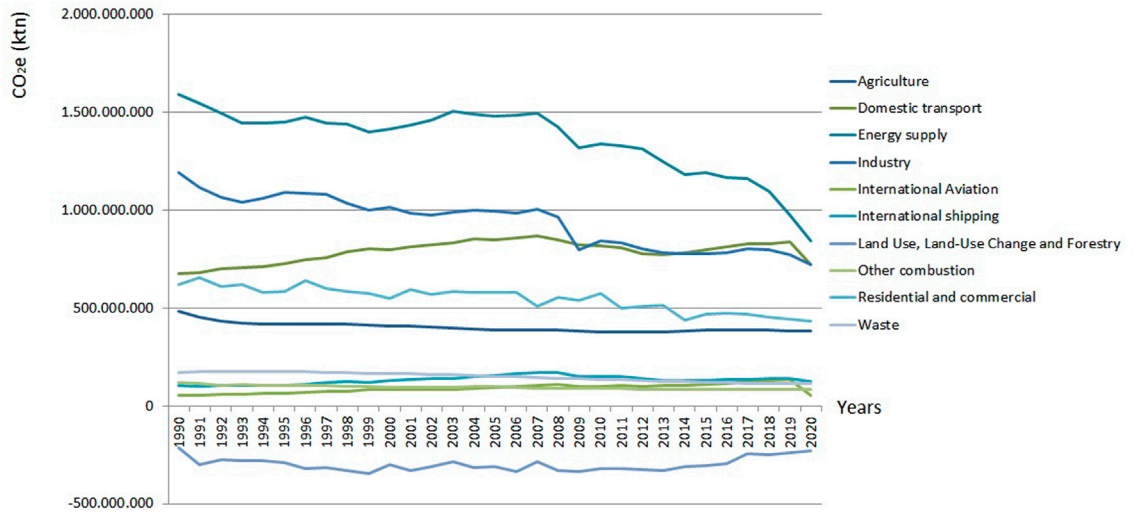

FIGURE 3
Cluster map for 2018 based on CO_2e (ktn).

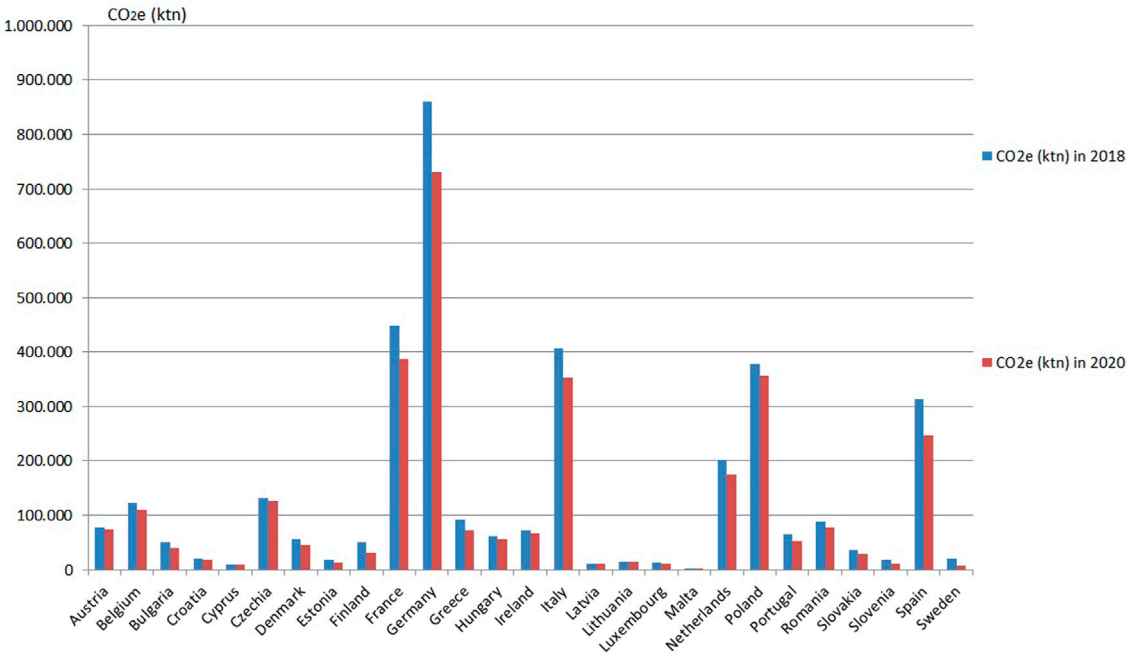

FIGURE 4
Cluster map for 2020 based on CO_2e (ktn).

ktn per total emissions and for 2020 it passed into Cluster 1 which has an average of 48,617 CO_2 ktn), Latvia (in 2018 it was in Cluster 2 with an average of approx. 12,185 CO_2 ktn per total emissions and for 2020 it passed into Cluster 3 which has an average of 16,131 CO_2 ktn), the Netherlands (in 2018 it was in Cluster 1 with an average of approx. 104,498 CO_2 ktn per total emissions and for 2020 it moved to Cluster 0 which has an average of 125,602 CO_2 ktn), Portugal (in 2018 it was in Cluster 0 with an average of approx. 90,026 CO_2 ktn per total emissions and for 2020 moved to Cluster 1 which has an average of 48,617 CO_2 ktn), Romania (was in 2018 in clusters 1 with an average of approx. 104,498 CO_2 ktn per total emissions and for 2020 it passed into Cluster 0 which has an average of 125,602 CO_2 ktn), Spain (in 2018 it was in Cluster 4 with an average of approx. 481,067 CO_2 ktn per total emissions and for 2020 it passed into Cluster 0 which has a mean of 125,602 CO_2 ktn).

TABLE 5 Cluster dynamics for EU27 countries regarding the CO_2e for years 2018 and 2020.

No.	Country	Cluster assignment in 2018	Cluster assignment in 2020	Comments (x - cluster updated)
1	Austria	0	0	
2	Belgium	0	0	
3	Bulgaria	0	1	x
4	Croatia	3	3	
5	Cyprus	2	2	
6	Czech Rep	0	0	
7	Denmark	1	1	
8	Estonia	2	2	
9	Finland	3	1	x
10	France	4	4	
11	Germany	4	4	
12	Greece	0	0	
13	Hungary	3	1	x
14	Ireland	1	1	
15	Italy	4	4	
16	Latvia	2	3	x
17	Lithuania	3	3	
18	Luxembourg	2	2	
19	Malta	2	2	
20	Netherlands	1	0	x
21	Poland	4	4	
22	Portugal	0	1	x
23	Romania	1	0	x
24	Slovakia	3	3	
25	Slovenia	2	2	
26	Spain	4	0	x
27	Sweden	3	3	

Applying an algorithm for classification process for the year 2020, respectively J48 algorithm, the correlation between the attributes used in the analysis can be determined (RRID:SCR_004363). Below is the pruned tree (decisional tree) that is obtained after running this algorithm.

J48 pruned tree

All_greenhouse_gases <= 65830
| All_greenhouse_gases <= 28357
| | Methane_CH4 <= 1894: cluster2 (5.0)
| | Methane_CH4 > 1894: cluster3 (5.0)
| All_greenhouse_gases > 28357: cluster1 (6.0)
All_greenhouse_gases > 65830
| All_greenhouse_gases <= 245671: cluster0 (7.0)
| All_greenhouse_gases > 245671: cluster4 (4.0)

Based on the decision tree, the main attributes based on which the countries are classified into clusters are total greenhouse gas emissions and based on Methane emissions. Based on this tree, the five rules for classifying the instances can be deduced, depending on the clusters. These rules are mentioned in Table 6.

The results obtained after running the algorithm and using the stratified cross-validation are mentioned in Table 7.

The detailed accuracy by Class Cluster with values Cluster 0, Cluster 1, Cluster 2, Cluster 3, Cluster 4 offered by the algorithm is the following (Table 8).

In Table 8 the used terms are (Ian et al., 2011): *TP Rate* and *FP Rate* (the true positives (TP) and true negatives (TN) are correct

TABLE 6 Tree based rules for classifying the instances.

Rule number	Condition	Consequence	Comment
1	**IF** *All_greenhouse_gases* ≤ 65,830	***THEN*** *Country allocated in Cluster 2*	Five countries are in this cluster
	AND *All_greenhouse_gases* ≤ *28,357*		
	AND *Methane_CH_4* ≤ *1894*		
2	**IF** *All_greenhouse_gases* ≤ 65,830	**THEN** *Countries allocated in* Cluster 3	Five countries are in this cluster
	AND *All_greenhouse_gases* ≤ *28,357*		
	AND *Methane_CH_4* > *1894*		
3	**IF** *All_greenhouse_gases* > *28,357*	**THEN** *Countries allocated in Cluster 1*	Six countries are in this cluster
4	**IF** *All_greenhouse_gases* > *65,830*	**THEN** *Countries allocated in Cluster* 0	Seven countries are in this cluster
	AND *All_greenhouse_gases* ≤ *245,671*		
5	**IF** *All_greenhouse_gases* > *65,830*	**THEN** *Countries allocated in Cluster 4*	Four countries are in this cluster
	AND *All_greenhouse_gases* > *245,671*		

TABLE 7 Results of the stratified cross-validation.

No.	Result name	Value (percent)	Details
1	Correctly Classified Instances	23 (85.18%)	
2	Incorrectly Classified Instances	4 (14.81%)	
3	Kappa statistic	0.8135	Compares the probability of agreement to that expected if the ratings are independent; usually the range values is between [0,1], one presenting complete agreement and zero meaning no agreement or independence (Yinglin (2020)
4	Mean absolute error	0.0593	A measure of errors between paired observations that express the same phenomenon
5	Root mean squared error	0.2434	Represents a used measure of the differences between values
6	Relative absolute error	18.3245%	A measure that compares a mean error (residual) to errors produced by a trivial or naive model
7	Root relative squared error	60.0042%	It is a measure computed based on the root mean squared error normalized by the root mean square value where each residual is scaled against the actual value
8	Total Number of Instances	27	

TABLE 8 Detailed accuracy by Class Cluster.

	TP rate	FP rate	Precision	Recall	F-measure	ROC area	Class
	0.857	0.05	0.857	0.857	0.857	0.904	Cluster 0
	0.833	0.048	0.833	0.833	0.833	0.893	Cluster 1
	0.8	0	1	0.8	0.889	0.9	Cluster 2
	0.8	0.045	0.8	0.8	0.8	0.877	Cluster 3
	1	0.043	0.8	1	0.889	0.978	Cluster 4
Weighted Avg	0.852	0.038	0.859	0.852	0.852	0.907	

classifications; *Precision* (also named positive predictive value, is the fraction of relevant instances (or objects) among the retrieved instances (or objects)); *Recall* (also called as sensitivity, is the fraction of relevant instances (or objects) that were retrieved); *F-Measure* (defined as the harmonic mean of precision (P) and recall (R)); *ROC Area* (it is a graph that is indicating the performance of a classification model at all classification thresholds).

The confusion matrix offered by the J48 algorithm is represented in Table 9. In this matrix, most of the values are on the main

TABLE 9 Confusion matrix for clusters (year 2020).

a	b	c	d	e	<-- *classified as*
6	0	0	0	*1*	*a = Cluster 0*
1	**5**	0	0	*0*	*b = Cluster 1*
0	0	**4**	1	*0*	c = Cluster 2
0	1	0	**4**	*0*	d = Cluster 3
0	0	0	0	**4**	e = Cluster 4

The meaning of the bold numbers represents the fact that those numbers are on the main diagonal. The bold numbers have bigger values which means that data classification was correctly done in a high degree.

diagonal, meaning that the most of the instances were correctly classified (23 out of 27).

Figure 5 shows the pruned tree, tree that has as the root the most significant element on the basis of which the classification of courts (countries) is made. The second most important attribute is the amount of Methane emitted into the atmosphere. The conditions described in the rules can be identified in the tree, starting from the root to the leaves (the elements on the last level). The figures in parentheses represent the number of courts classified taking into account the above conditions in the tree.

4.2 Cluster analysis based on greenhouse gas emissions for the industry areas for the countries from European Union

In this section, following the mining analysis, the authors want to find out the answer to the fourth research question, respectively, which are the most similar sectors of the economy in terms of carbon emissions (CO_2) in 2020 and what are the correlations between them?

For this analysis, data were taken from the European Environment Agency website (EEA, 2022). Figure 6 shows the evolution from 1990 to 2020 of total greenhouse gas emissions for several sectors of the economy, respectively: agriculture, domestic transport (the movement of goods or people, either by air or land, within the national borders of a country.), energy supply, industry, international aviation, international shipping, land use and forestry, residential and commercial, waste and other combustion sources. It can be seen that starting with year 2019, almost every analyzed source tends to decrease in value which means that the measures recommended by the European Union through Green Deal are embraced by the countries despite the fact that many of them for the moment are only proposals.

Taking into account the fourth research question, the Simple K-Means algorithm was applied for the following sectors: agriculture, domestic transport, energy supply, industry, international aviation, international shipping, residential and commercial, waste and other combustion sources. The results for year 2020 are as follows:

Cluster 0–the most representative sector is Agriculture with the value around 408,685,497 CO_2 ktn. The sectors from this cluster are Agriculture and Residential and commercial.

Cluster 1–the most representative sector is Domestic transport with the value around 720,441,152.5 CO_2 ktn. The sectors from this cluster are Domestic transport and Industry.

Cluster 2–the most representative sector is Energy supply with the value around 842,906,717 CO_2 ktn. The sector from this cluster is Energy supply.

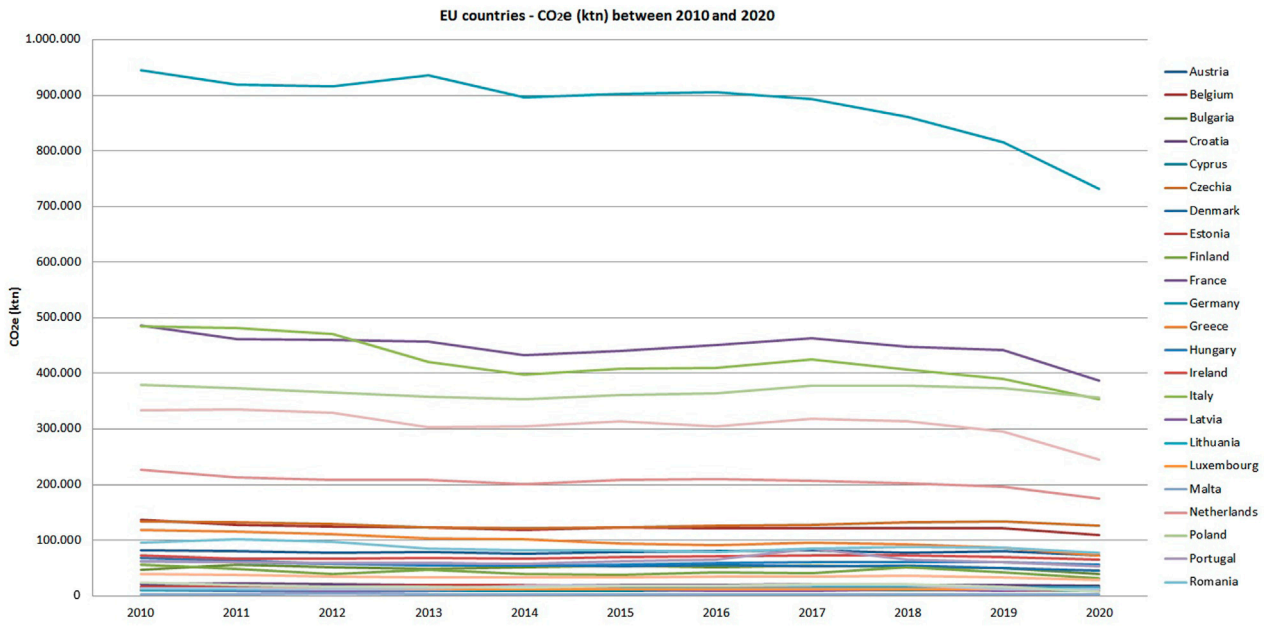

FIGURE 5
Pruned tree for the greenhouse gas emissions for 2020.

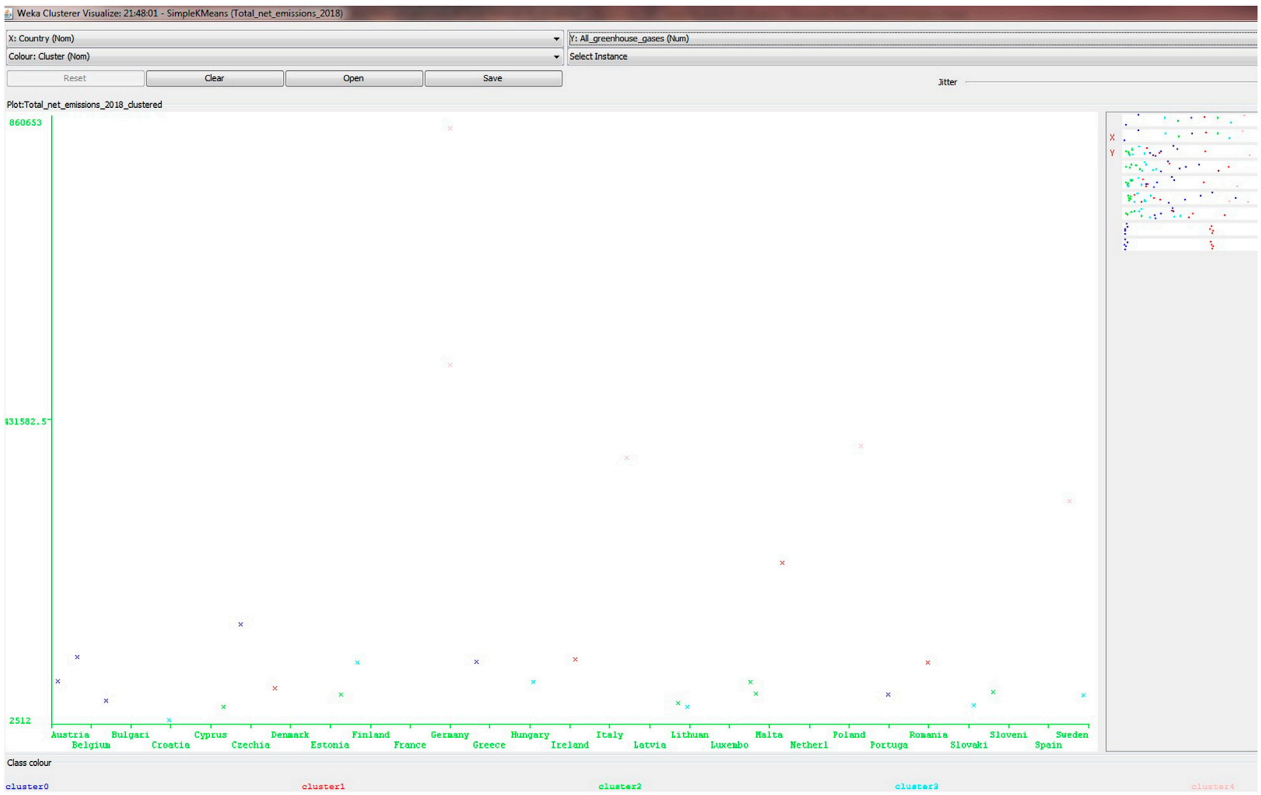

FIGURE 6
EU27–Economy sectors - CO_2e (ktn) in 2018 and 2020. Data source (EEA, 2022).

Cluster 3–the most representative sector is International aviation with the value around 93,870,858 CO_2 ktn. The sectors from this cluster are International aviation, International shipping, Waste, and Other combustion.

In order to obtain a set of rules for the mentioned economy sectors, a data set with values between year 1990 and 2020 (31 years) was analyzed regarding the total greenhouse gas emissions. The Nearest-neighbor-like algorithm (NNge) was used. The generated rules are mentioned in Table 10. The numbers between brackets at the end of each rule represent the number of instances that are following that rule. Based on these rule, correlations between the values of the emissions may highlighted.

Analyzing the rules obtained above after running the Nearest-neighbor-like algorithm, we can observe for the 31 years considered for the analysis, the correlations between the economic sectors taken into account. Based on the number in the brackets at the end of each rule, it can be seen that the rule related to Cluster 0 applies for 10 years of the analysis, the rule related to Cluster 1 for 7 years, the rule related to Cluster 2 for 1 year and the rule related to Cluster 3 for 13 years.

5 Discussion

Based on the data analysis, the answers to the research questions are commented below.

Therefore, to the first question, namely, "What are the main groups (clusters) of countries in the European Union for the years 2018 and 2020 in terms of total greenhouse gas emissions, Carbon dioxide, Methane, Fluorinated gases (F-gases), Nitrous oxides?" it can be stated that for the 27 countries considered in the analysis, 5 groups (clusters) were identified, the representativeness within them being relatively uniform. The cluster data mining analysis was done for 2018 and 2020 in order to highlight whether the recommendations made under the Green Deal strategy had positive effects or not. It can be seen that for the countries in Cluster 0 in 2018, the values tend to become higher in 2020 (also in Cluster 0). However, the other clusters and countries tend to have lower values in general. It should also be taken into account that during this period the COVID-19 pandemic has reduced the dynamics of economies both at the European and international level. The most representative country for each group was in 2018: Cluster 0 - Austria, Cluster 1 - Denmark, Cluster 2 - Cyprus, Cluster 3 - Croatia and Cluster 4 - France. It can be seen that in Cluster 4, the values for greenhouse gas emissions are the highest, where the countries with the most developed economies are also distributed. At the opposite pole, there are the countries from Cluster 2, where the lowest values are recorded. For 2020, the most representative were: Cluster 0–Austria, Cluster 1–Bulgaria, Cluster 2–Cyprus, Cluster 3–Croatia and Cluster 4–France. The cluster with the lowest values is Cluster 2 and with the highest values Cluster 4. Also for the year 2020, the relative balanced distribution in the identified clusters can be observed. From the point of view of the representative countries for each cluster, the difference between

TABLE 10 Rules for economy sectors.

No.	Cluster	Conditions	Number of instances that are following the rule
1	Cluster 0	**IF**	10
		3.85E8 ≤ Agriculture ≤ 4.17E8 AND 7.55E8 ≤ Domestic_transport ≤ 8.56E8 AND 1.39E9 ≤ Energy_supply ≤ 1.50E9 AND 9.74E8 ≤ Industry ≤ 1.07E9 AND 7.15E7 ≤ International_Aviation ≤ 1.00E8 AND 1.19E8 ≤ International_shipping ≤ 1.64E8 AND -3.43E8 ≤ Land_Use_and_Forestry ≤ -2.85E8 AND 9.36E7 ≤ Other_combustion ≤ 1.02E8 AND 5.50E8 ≤ Residential_and_commercial ≤ 5.99E8 AND 1.48E8 ≤ Waste ≤ 1.72E8	
2	Cluster 1	**IF**	7
		4.17E8 ≤ Agriculture ≤ 4.82E8 AND 6.72E8 ≤ Domestic_transport ≤ 7.45E8 AND 1.44E9 ≤ Energy_supply ≤ 1.59E9 AND 1.03E9 ≤ Industry ≤ 1.18E9 AND 5.30E7 ≤ International_Aviation ≤ 6.87E7 AND 1.00E8 ≤ International_shipping ≤ 1.09E8 AND -3.21E8 ≤ Land_Use_and_Forestry ≤ -2.13E8 AND 1.03E8 ≤ Other_combustion ≤ 1.17E8 AND 5.77E8 ≤ Residential_and_commercial ≤ 6.55E8 AND 1.72E8 ≤ Waste ≤ 1.77E8	
3	Cluster 2	**IF**	1
		Agriculture = 3.82E8 AND Domestic_transport = 7.21E8 AND Energy_supply = 8.42E8 AND Industry = 7.19E8 AND International_Aviation = 5.58E7 AND International_shipping = 1.22E8 AND Land_Use_and_Forestry = -2.29E8 AND Other_combustion = 8.47E7 AND Residential_and_commercial = 4.34E8 AND Waste = 1.12E8	
4	Cluster 3	**IF**	13
		3.75E8 ≤ Agriculture ≤ 3.89E8 AND 7.73E8 ≤ Domestic_transport ≤ 8.65E8 AND 9.72E8 ≤ Energy_supply ≤ 1.49E9 AND 7.72E8 ≤ Industry ≤ 1.00E9 AND 9.85E7 ≤ International_Aviation ≤ 1.32E8 AND 1.27E8 ≤ International_shipping ≤ 1.71E8 AND -3.36E8 ≤ Land_Use_and_Forestry ≤ -2.37E8 AND 8.30E7 ≤ Other_combustion ≤ 9.09E7 AND 4.40E8 ≤ Residential_and_commercial ≤ 5.73E8 AND 1.13E8 ≤ Waste ≤ 1.44E8	

2018 and 2020 is that for Cluster 1, it is not Denmark (218) but Bulgaria (2020).

The utility of such an analysis lies in the fact that knowing and understanding better the similarities between the countries and identifying the group to which each country belongs, political and environmental strategies can be easily adopted to target and apply to several similar countries. The analysis carried out takes into account only the total greenhouse gas emissions, Methane (CH_4), Carbon dioxide (CO_2), Fluorinated gases and Nitrous oxides (N_2O). These elements are the subject of this analysis.

For the second question, namely, "What is the dynamics of the groups identified in the first question from the point of view of the years achieved, 2018 and 2020″, it can be stated that 8 countries out of 27 had a different behavior compared to the others, changing their group in which they were initially allocated in 2018. Therefore, we may speak about a 30% of the countries which have had a different behavior regarding these two periods of time. The countries that behaved differently were Bulgaria, Finland, Hungary, Latvia, Netherlands, Portugal, Romania and Spain. For some countries, it can be stated that they recorded higher values in 2020 compared to 2018, such as those in Cluster 0. Other clusters recorded decreases in greenhouse gas emissions. The countries that were allocated differently for 2018 and 2020 were mentioned in the breakdown of the clusters for each year.

Such an analysis is useful to highlight the way in which some countries manage to face the challenges imposed by the necessity to reduce greenhouse gas emissions as well as the one imposed by unexpected situations, such as the COVID-19 pandemic.

The third research question that was addressed is "What are the characteristics of the profiles of the identified groups for the year 2020 in terms of the types of gases emissions?", it can be stated that the total greenhouse gas emissions and the Methane gas emissions are the most significant attributes in order to obtain the classification for the EU countries. Based on these two elements, a set of five rules were deduced regarding conditions based on which countries could be assigned into a group based on their values. The rules are obtained based on the J48 algorithm and express the conditions that a country must fulfill for the values regarding the CO_2e (ktn) and Methane gas emissions. The correctness of the classification process, namely, 23 countries out of 27 (over 85%) is also showed by the confusion matrix which has the highest values on the main diagonal.

The fourth research question is "Which are the economic sectors most similar in terms of carbon emissions (CO_2) in 2020 and what are the correlations between them?". In order to answer to this question, information was collected on sectors such as agriculture, domestic transport, energy supply, industry, international aviation, international shipping, land use and forestry, residential and commercial, waste and other combustion sources. In order to group these sectors a cluster algorithm was used. There were identify four groups, namely, the first one (cluster 0) consisting of Agriculture and Residential and

commercial, the second (Cluster 1) consisting of Domestic transport and Industry, the third (Cluster 2) made up of Energy_supply and the fourth (Cluster 3) made up of International aviation, International shipping, Waste, and Other_combustion. In order to be able to identify certain correlations between these sectors, a period of 31 years was considered, respectively between 1990 and 2020. From the point of view of values, 4 rules were identified, three of them applying to several years, (respectively 10, 7 and 13 years) and one for a single year. Within each rule, the minimum and maximum values are mentioned for each sector considered in the analysis and the conditions must be fulfilled simultaneously.

The European Union is a pioneer in terms of developing and implementing a strategy to target the most important areas that directly affect life, making them priorities. Through the European Commission, the Green Deal strategy was proposed, which aims to take immediate and concrete actions that will lead to a sustainable development and increased quality of life in Europe and not only. Among these actions are the reduction of greenhouse gas emissions as much as possible, the increase of water quality, the number of renewable energy sources and low carbon fuels, the modernization of industries to become sustainable, the creation of a legal framework for the creation, use and storage of substances and chemical products, collection by product type of household waste, *etc.*

The reduction of greenhouse gas emissions is one of the main objectives of the Green Deal strategy because it has a direct impact on climate change. In recent years, due to climate change, there have been more and more extreme phenomena that have increased in intensity and frequency throughout the world, causing billions of euros worth of damage. For the most effective implementation of the solutions to combat greenhouse gas emissions, the quantification of the effects of the implemented solutions must be taken into account, as well as the effect these solutions have on the citizens. The application and monitoring of the solutions implies an allocation of resources that each country must assume, a large part of the material and financial support coming from the European Parliament. The good news in this regard is that the technologies that can be used to reduce greenhouse gas emissions exist and can be used successfully. These aim at solutions regarding: changing fossil fuels with renewable sources, increasing the efficiency of the energy used, and discouraging carbon emissions by creating a legal framework in which the price on them to be very high.

6 Conclusion

Greenhouse gas emissions represent one of the most important factors in terms of climate change. All over the world there are initiatives to combat and reduce these emissions. As far as the European Union is concerned, the strategy proposed by it is the Green Deal strategy which has a series of objectives with a direct impact on the environment, its sustainable development as well as the quality of life. This article describes the main aspects of the Green Deal strategy from the point of view of the general purpose and the proposed objectives. Also, taking into account the important role of greenhouse gas emissions, a cluster-type data mining analysis was carried out to identify, in a first stage, the groups of countries with similar behavior in relation to the amount of CO_2 emitted into the atmosphere (the total quantity emitted as well as the quantities of Carbon dioxide, Methane, Fluorinated gases and Nitrous oxides) for the years 2018 and 2020 were taken into account. Next, the dynamics of the created groups were identified, in order to identify the countries that were different from the point of view of the group in which they were initially included. Based on the groups of countries created, the profiles of these groups were identified for the year 2020. In order to identify a correlation between the main sectors of the economy that contribute to greenhouse gas emissions, a data analysis was carried out for a period of 31 years (the period between the 1990 and 2020) to identify the correlations between these sectors and the degree of greenhouse gas emissions. A set of rules was obtained that can be applied for the 31 years, taking into account the total greenhouse gas emissions from each sector.

Summarizing the main findings of the research, it may conclude that.

- At the EU level, it was identified a group of 5 clusters based on the CO_2e (ktn).
- Analyzing these clusters for years 2018 (before Greed Deal) and 2020 (after 1 year of Green Deal) it can be mentioned that the CO_2e (ktn) was reduced. An important role in this period had also the COVID-19 pandemic;
- Having the comparison between the 5 clusters for the 2018 and 2020, it can be said that only one cluster had higher values for the CO_2e (ktn) in 2020 than it has had in 2018. The rest of the four clusters have lower values in 2020 than they had in 2018.
- Regarding the dynamics of the clusters, it can be mentioned that from 27 countries, 8 countries have had a different behavior compared to the others regarding the CO_2e (ktn);
- In order to identify profiles characteristics for the cluster groups for 2020 in terms of types for gases emissions, it can be mentioned that the total greenhouse gas emissions and the Methane gas emissions are the most significant. Based on them, a set of five rules was identity to classify the EU countries;
- For the main economy sectors, based on a cluster analysis, four clusters were identified based on the CO_2 (ktn). In order to establish correlations between these sectors, a time period of 31 years was analyzed. As a result, a set of four rules were identify, three of them could be apply to several years and one for a single year.

A future research work may consist of a more detailed approach, in order to identify groups of countries with similar characteristics. In the data mining cluster analysis may be introduced information about other elements that may influence the solutions proposed within the Green Deal strategy, such as, for example: how open are people to apply the recommended measures at the individual/family level, the openness of managers of small and medium enterprises to implement new technologies and to rethink the activity of the

companies, the solutions proposed by the mayors to use energy in the most efficient way to heat the buildings.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

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.

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Educational fields of higher education graduates in European Union

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The processes of automation and globalization are resizing workplaces through their changes. A picture of the labor market can be provided by the educational fields of the graduates. Thus, depending on the educational field, the situation regarding the distribution of bachelor's graduates is analyzed in the article. The importance of the quality of the education and vocational training processes can be considered to be the basis of addressing the major challenges that are manifesting worldwide. Economic and social pressures influence the development of skills and competencies even for higher education. Training for the purpose of employment also contributes to increasing employability. The degree of access to jobs is higher when the level of education is higher. For the age group 15 to 64, this article presents the share of graduates having an education level between 5 and 8. Quality education can contribute to sustainable development. Thus, to identify solutions to problems that may arise in a community, the contribution of education can increase by increasing the life quality of the members from that community. In this context, for the 30–34 age group, at European level, the evolution of graduates with a tertiary level of education is analyzed. For employers, it is very important to know both the level of education and especially the fields in which they are trained. This is one of the reasons why the authors of the study carried out this analysis. Taking into account the classification of graduates according to the educational field, the research presents the situation for each of the five fields for which in 2020 there were the most numerous bachelor's graduates.

KEYWORDS

tertiary education, graduates, European Union, higher education, globalization

1 Introduction

A flexible learning process can influence employability. Technological changes require periodical updates of knowledge, skills, and abilities (Angheluţă et al., 2021). At the same time, the chances of graduates getting a job increase if the studies completed are at tertiary level (Burlacu et al., 2021). Their employment rates are higher than those of graduates with lower training levels (European Commission, 2019).

Education is an essential tool for achieving sustainability goals (Goritz et al., 2019). Furthermore, the 2030 Agenda for sustainable development, through the fourth objective,

foresees the need to ensure quality education, including tertiary education (United Nations, 2015).

It is believed that the economic growth of a society is stimulated by graduates with higher education. Several disciplines and educational fields are considered with regards to the labor force integration (Rădulescu et al., 2020). How students adapt to the academic requirements, as well as their psychological and sociocultural adaptability, is very important for their educational process (Han et al., 2022). The inconsistencies between graduates' skills and the labor market requirements lead to demands for new skills (OECD, 2016). Thus, the acquisition of new knowledge and skills can lead to the decrease of these inconsistencies (European Commission, 2018a).

Acquiring the values, attitudes and behaviors that lead to sustainable behaviors during academic studies has a social, economic and environmental impact (Sonetti et al., 2019). Universities can develop certain processes of organizational change by integrating sustainable development in all their fields of activity (Vargas et al., 2019). Thus, emphasizing initiative and adaptability in educational programs implies certain structural and systematic changes (Lambrechts et al., 2018).

Companies can become more competitive if they support employees in their efforts to develop competencies (European Centre for the Development of Vocational Training (Cedefop), 2019). Academic training needs to be continued by acquiring a postgraduate qualification (Androniceanu and Burlacu, 2017). The ongoing challenges lead to an increased level of expertise among graduates of higher education (Mateos-González and Wakeling, 2022). The efficient use of company resources, as well as the creation of green jobs, can lead to an increase in turnover and profit (Luca et al., 2019).

The changes brought to educational practices and policies have led to higher interest in sustainable development education (O'Flaherty and Liddy, 2018).

Quality education can lead to sustainable development (Alpopi et al., 2022). Adapting to labor market changes is a necessity for educational systems (Profiroiu et al., 2020). Automated and digitized production processes put pressure on the education level of workers (Burlacu et al., 2018). Thus, the educational field is influenced by transformations occurring in the economical, technological and social fields (Burlacu et al., 2013).

Both the level of education, and especially the fields in which the graduates are trained, are very important for employers. Labor mobility is high at European level. Thus, the study contributes to the knowledge of these indicators, coming to the support of employers in the respective fields.

2 Results

Investments in new competencies allow an increasing capacity for professional insertion (European Commission, 2018b). Partnerships between academia and companies lead to an increased number of jobs performed by highly qualified workers (European Commission, 2017).

For the member countries of the European Union, the article presents an analysis of the situation regarding the distribution of bachelor's graduates, based on the educational field. Thus, at the level of the European Union, for the year 2020, the distribution of level 6 graduates according to the educational field is shown in Figure 1.

From the previous figure one can observe that, for the year 2020, the majority of graduates come from the fields of business, administration and law (24.0%). This is followed by engineering, manufacturing and construction (13.8%), health and welfare (12.3%), education (10.7%), arts and humanities (10.6%).

Considering the classification of graduates by their educational field, the research continues with a presentation of the situation for each of the five fields for which in 2020 there were the most numerous bachelor's graduates. Thus, at the level of the European Union, in 2020, 534,289 people are graduates of business, administration and law. The most graduates were from: Germany (105,053 people), France (91,957 people), Poland (69,100 people), Spain (41,703 people).

For the field of engineering, manufacturing and construction, in 2020, there were 307,718 people who graduated with a bachelor's degree. The countries that produced the most graduates in this field are: Germany (94,747 people), Poland (31,724 people), Italy (31,650 people), France (21,079 people).

In 2020, in the field of health and welfare, 273,432 people are graduates. Most graduates come from: Poland (43,271 people), France (39,292 people), Spain (24,081 people), Italy (23,326 people).

In the field of education, the number of graduates for the year 2020 was 237,871. The countries with the most graduates were: Italy (46,755 people), Germany (40,850 people), Poland (39,566 people), Spain (34,663 people).

In 2020, 235,742 people are graduates in arts and humanities. The number of graduates was high in: Italy (48,145 people), France (45,112 people), Spain (25,202 people), Germany (22,664 people).

In 2020, the countries that had more than 250,000 bachelor's graduates were: Germany (363,667 graduates), France (290,533 graduates), Poland (275,930 graduates), Italy (264,990 graduates).

Therefore, in 2020, in Germany, the distribution of bachelor's graduates according to educational field is shown in Figure 2 (graduates).

From this figure it can be observed that 79.4% of the graduates graduated from: business, administration and law (105,053 graduates); engineering, manufacturing and construction (94,747 graduates); education (40,850 graduates); social sciences, journalism and information (23,807 graduates); arts and humanities (22,664 graduates).

The distribution of bachelor's graduates according to educational field, in 2020, for France, is shown in Figure 3.

It is noted that 81.3% of the graduates graduated from: business, administration and law (91,957 graduates); arts and humanities (45,112 graduates); health and welfare (39,292 graduates); natural sciences, mathematics and statistics (29,254 graduates); social sciences, journalism and information (30,013 graduates).

The distribution of bachelor's or equivalent graduates according to educational field, for Poland, in 2020, is shown in Figure 4.

It is noted that 67.7% of the graduates graduated from: business, administration and law (69,100 graduates); health and welfare (43,271 graduates); education (39,566 graduates); engineering, manufacturing and construction (31,724 graduates).

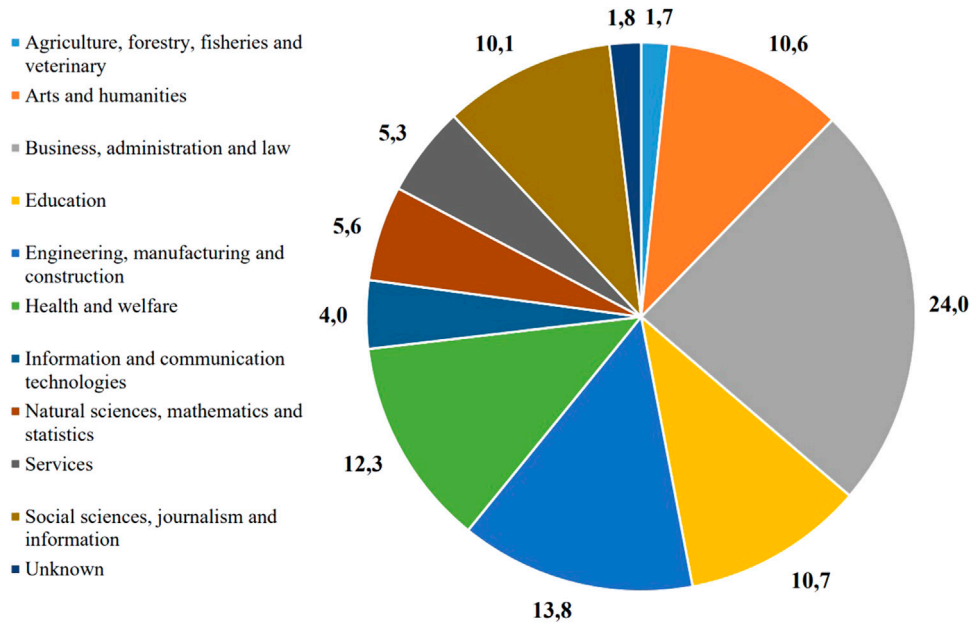

FIGURE 1
Distribution of level 6 graduates by educational field, 2020 (%). Source: own processing according to data published by Eurostat, 2022.

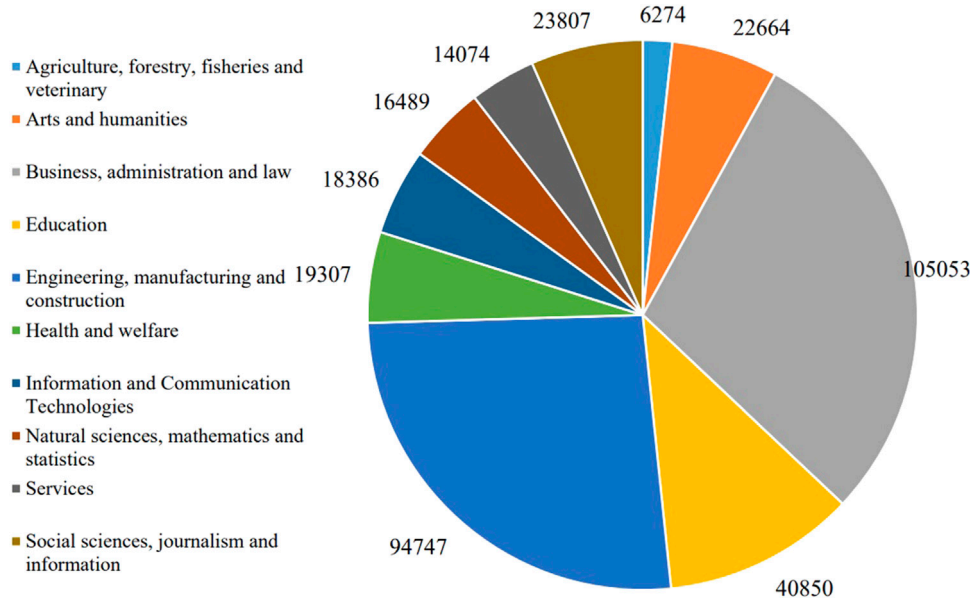

FIGURE 2
Distribution of bachelor's graduates by educational field, Germany, 2020. Source: own processing according to data published by Eurostat, 2022.

Figure 5 shows the distribution of bachelor's graduates according to the educational field for Italy, in 2020. It is noted that 77.0% of the graduates graduated from: arts and humanities (48,145 graduates); education (46,755 graduates); business, administration and law (38,796 graduates); social sciences, journalism and information (38,779 graduates); engineering, manufacturing and construction (31,650 graduates).

The creation of new jobs contributes to an increased quality of life. At the same time, production and consumption methods can change the consumption behavior of the population (Luca et al., 2019).

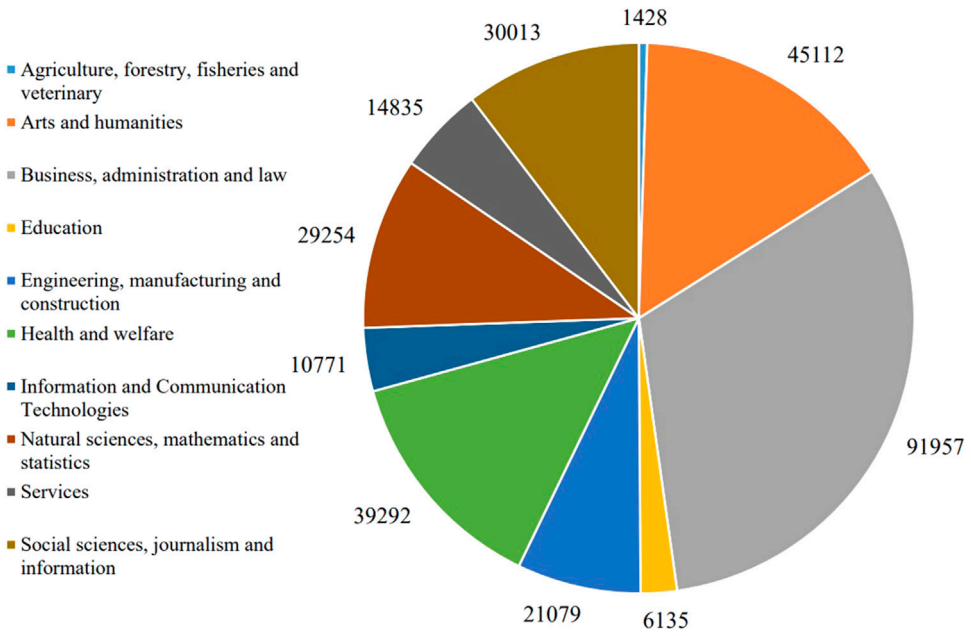

FIGURE 3
Distribution of bachelor's graduates by educational field, France, 2020. Source: own processing according to data published by Eurostat, 2022.

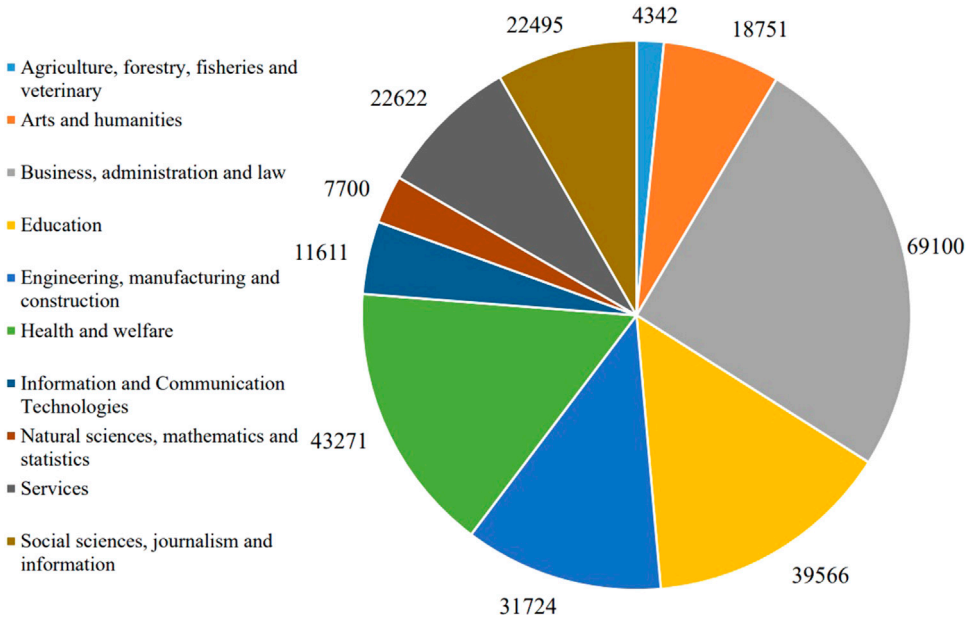

FIGURE 4
Distribution of bachelor's graduates by educational field, Poland, 2020. Source: own processing according to data published by Eurostat, 2022.

Table 1 shows the 2012–2021 comparative situation of the share of people in the 15–64 age group, graduates of the tertiary level of education (levels 5–8).

From the data presented, it can be observed that, at the European level, the share of people in the age group of 15–64 years, graduates of the tertiary level of education, increased from 23.2% (in 2012) to

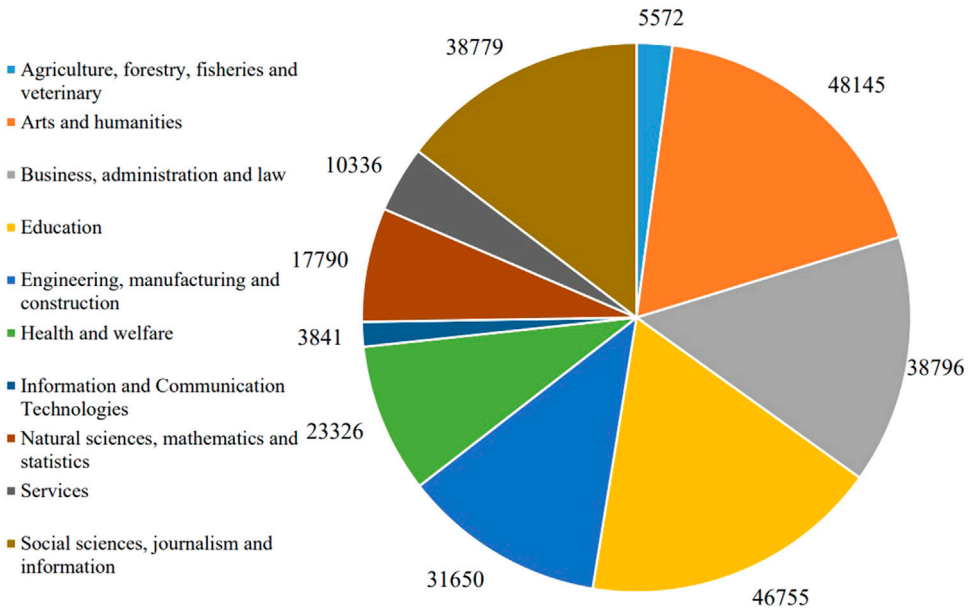

FIGURE 5
Distribution of bachelor's graduates by educational field, Italy, 2020. Source: own processing according to data published by Eurostat, 2022.

29.5% (in year 2021). The most significant increases were in: Austria (+14.9%), Malta (+12.7%), Slovenia (+12.4%).

In 2021, the countries with the highest shares of people in the 15–64 age group, graduates of the tertiary education level, are: Ireland (45.2%), Luxembourg (44.5%), Cyprus (41.9%), Lithuania (39.8%), Belgium (39.7%), Sweden (39.7%). Also, the countries with the lowest shares are: Romania (16.4%), Italy (17.8%), Croatia (21.8%), Czech Republic (23.4%), Slovakia (24.7%). Thus, in 2021, in three-quarters of the European Union member countries, at least one out of four people in the 15–64 age group is a tertiary education graduate. The highest values are observed in Ireland, Luxembourg and Cyprus, where approximately one in two people in the 15–64 age group has completed tertiary education. The lowest values are found in Romania, where approximately one in six people in the 15–64 age group is a tertiary education graduate.

Another aspect related to the sustainability of universities derives from the share of tertiary education graduates for the 30–34 age group. Thus, from the data presented in the previous table, it can be concluded that, compared to 2012, the most significant increases in 2021 were registered in: Malta (+17.4%), Austria (+16.9%), Slovakia (+16.5%), Portugal (+15.9%), Greece (+13.1%).

Also, in 2021, the highest values are observed in: Luxembourg (62.5%), Ireland (62.0%), Cyprus (61.5%), Lithuania (60.2%), the Netherlands (53.4%), Denmark (52.8%), Sweden (51.9%). At the same time, for the 30–34 age group, it is observed that in 2012 only Ireland (52.2%) had a percentage of over 50% of the population graduating from the tertiary education level.

Another aspect related to the sustainability of universities derives from the share of tertiary education graduates for the 30–34 age group. Thus, from the data presented in the previous table, it can be concluded that, compared to 2012, in 2021, the most significant increases were registered in: Malta (+17.4%), Austria (+16.9%), Slovakia (+16.5%), Portugal (+15.9%), Greece (+13.1%). Also, in 2021, the highest values are observed in: Luxembourg (62.5%), Ireland (62.0%), Cyprus (61.5%), Lithuania (60.2%), the Netherlands (53.4%), Denmark (52.8%), Sweden (51.9%). At the same time, for the 30–34 age group, it is observed that in 2012 only Ireland (52.2%) had a percentage of over 50% of the population graduating from the tertiary education level.

In 2012, values below 25% were registered in: Romania (21.7%), Italy (21.9%), Croatia (23.1%), Slovakia (23.7%), the Czech Republic (25.6%). In 2021, values below 25% were recorded only in: Romania (24.8%). This means that approximately one person in four in the 30–34 age group has completed tertiary education. At the same time, in 2021, for seven countries in the European Union, approximately one person out of two in the 30–34 age group is a tertiary education graduate (Luxembourg, Ireland, Cyprus, Lithuania, Holland, Denmark, Sweden).

3 Discussion

Sustainable development takes into consideration both the social, and the economic and environmental domains. They are interconnected and equally important. The sustainability of an institution refers to its role in protecting the environment, ensuring social justice and supporting economic growth. Thus, sustainable development requires an integration between society, economy and environment. Sustainable universities can use this approach (Lukman et al., 2010; Ragazzi and Ghidini, 2017).

In terms of sustainability, universities can make their mark right from the teaching and learning process. The focus of teaching and learning methods on different types of learning—experiential, active,

TABLE 1 Comparative situation 2012–2021 of the share of people in the age group 15–64 years, respectively 30–34 years, graduates of the tertiary education level (levels 5–8) (%).

Countries	Age group 15–64 years				Age group 30–34 years			
	2012	2015	2018	2021	2012	2015	2018	2021
European Union	23.2	25.2	27.1	29.5	34.5	37.3	39.4	41.6
Belgium	31.3	32.7	36.0	39.7	43.9	42.7	47.6	49.9
Bulgaria	20.7	24.1	24.8	25.9	26.9	32.1	33.7	32.7
Czechia	17.0	19.8	21.7	23.4	25.6	30.1	33.7	36.5
Denmark	28.5	30.2	32.6	34.9	43.2	45.7	48.7	52.8
Germany	24.9	23.8	25.2	27.0	31.8	32.3	34.9	37.8
Estonia	32.1	32.0	34.1	36.0	39.5	42.7	44.6	43.1
Ireland	35.7	39.0	40.5	45.2	52.2	53.8	56.3	62.0
Greece	22.9	25.4	27.7	30.1	31.2	40.4	44.3	44.3
Spain	30.0	32.1	34.0	36.5	41.5	40.9	42.4	46.7
France	27.7	30.5	32.8	36.3	43.3	45.1	46.2	49.5
Croatia	15.8	19.7	22.0	21.8	23.1	30.8	34.1	33.7
Italy	13.9	15.5	17.1	17.8	21.9	25.3	27.8	26.8
Cyprus	35.0	36.4	39.4	41.9	49.9	54.5	57.1	61.5
Latvia	25.2	28.1	30.1	34.2	37.2	41.3	42.7	47.7
Lithuania	28.6	33.2	36.1	39.8	48.6	57.6	57.6	60.2
Luxembourg	33.4	35.2	38.3	44.5	49.6	52.3	56.2	62.5
Hungary	19.0	20.9	21.7	25.4	29.8	34.3	33.7	35.5
Malta	16.6	19.9	24.6	29.3	26.3	29.1	34.8	43.7
Netherlands	28.6	30.5	33.0	37.5	42.2	46.3	49.4	53.4
Austria	16.9	28.1	30.1	31.8	26.1	38.7	40.7	43.0
Poland	21.5	24.4	27.2	29.1	39.1	43.4	45.7	45.9
Portugal	16.7	20.7	22.5	28.3	27.8	31.9	33.5	43.7
Romania	13.5	15.0	15.5	16.4	21.7	25.6	24.6	24.8
Slovenia	23.0	26.6	28.7	35.4	39.2	43.4	42.7	49.2
Slovakia	17.0	18.9	22.0	24.7	23.7	28.4	37.7	40.2
Finland	32.8	35.5	37.3	35.5	45.8	45.5	44.2	44.9
Sweden	30.1	34.0	37.1	39.7	47.9	50.2	51.8	51.9

Source: own processing according to data published by Eurostat, 2022.

participatory, reflective, based on practice—can lead to the acquisition of competencies for sustainable development. Also, in order to evaluate these skills, teaching and learning methods should take into account a transdisciplinary approach, a problem-solving approach, a creativity approach. In this way, the link between skills and competencies, and sustainability can be justified (Wals and Jickling, 2002; Sterling, 2004; Wals, 2010; Lambrechts and Van Petegem, 2016; Fuertes-Camacho et al., 2019). Introducing such different teaching and learning methods can ensure that the skills students acquire are those that future jobs will demand.

A sustainable and qualitative teaching can make educational activities contribute to the sustainability of a university. The application and development of innovative forms of learning can introduce changes in higher education (Fülöp et al., 2022). In recent period, it is observed that the competencies related to sustainable development are increasingly integrated into study programs (Watson et al., 2013; Robina-Ramírez et al., 2020; Estrada Guillén et al., 2022).

The transition to sustainability is one of the responsibilities that universities can assume. Knowledge that students acquire during their studies can enable them to act and think in sustainable ways. During their professional career, graduates can approach solving

tasks through the lens of sustainable development. Thus, it can be considered that the whole society benefits from this approach (Xue, 2022).

Increased learning mobility, as well as increased academic cooperation, can contribute to the acquisition of skills that allow easy access to the labor market (Burlacu and Grosu, 2009; Ladaru et al., 2022).

From the analysis carried out, it can be observed that the first three fields for which the number of graduates in 2020 was the most numerous are: business, administration and law (24.0%), engineering, manufacturing and construction (13.8%), health and welfare (12.3%). In 2020, at the level of the European Union, graduates of these three fields represented approximately half of all graduates (50.1%). Also, the field of business, administration and law was in first place for three of the four analyzed countries, and for Italy (for which the field of Arts and Humanities was in first place) this field was the third. At the level of the European Union, most graduates came from Germany, France and Poland.

From the data presented, it can be observed that at the European level, the share of people in the age group of 15–64 years, graduates of the tertiary level of education, increased from 23.2% (in 2012) to 29.5% (in year 2021). In 2021, the countries with the highest shares of people in the 15–64 age group, graduates of the tertiary education level, are: Ireland (45.2%), Luxembourg (44.5%), Cyprus (41.9%), Lithuania (39.8%), Belgium (39.7%), Sweden (39.7%). Also, the countries with the lowest shares are: Romania (16.4%), Italy (17.8%), Croatia (21.8%), Czech Republic (23.4%), Slovakia (24.7%).

Regarding the tertiary level of education for people in the 30–34 age group, in 2021, an annual share of graduates higher than 50% was found for the following countries: Luxembourg, Ireland, Cyprus, Lithuania, the Netherlands, Denmark, Sweden. In 2021, only in Romania approximately one out of four persons in the age group 30–34 years will graduate from the tertiary level of education. At the same time, for seven countries in the European Union, approximately one person out of two in the 30–34 age group is a tertiary education graduate (Luxembourg, Ireland, Cyprus, Lithuania, Holland, Denmark, Sweden).

Dynamic, intercultural and transnational work environments enable recent higher education graduates to respond to sustainability challenges. The development and application of new cutting-edge technology will only be possible with the help of graduates who have acquired high-level skills (Burlacu and Jiroveanu, 2009).

However, we can consider that career guidance activities had prior to accessing higher education can be useful for future students. Changes in production processes due to automation means that new jobs require higher training. The implementation of high manufacturing technologies can be achieved through highly skilled personnel. However, for some jobs, the tasks will not require high level skills. Even if the trend in the shares of tertiary education graduates is increasing, it will also be necessary to cover jobs with low levels of training. At the same time, the influence on jobs that artificial intelligence will have in the future should not be excluded.

Regarding graduates by educational fields, one of the limitations of the analysis carried out may be the existence on the website of the European Commission that deals with statistics (EUROSTAT, 2022) of information relative to the year 2020. Another limitation is the presentation of the situation only for five educational fields for which there were the most numerous bachelor's graduates. Also, future studies may take into account an analysis over time of the weight of graduates according to educational fields. Further research may consider both country-level comparative assessments of educational fields and the extent to which recent tertiary graduates initiate business start-ups.

It can be concluded that there is a major interest in completing the highest possible level of education. Over the course of a lifetime, upskilling leads to higher employment rates. Thus, participation to continuous professional education and training programs contributes to employability (European Commission, 2022). The fields in which the graduates are trained, as well as the level of education, are benchmarks that employers take into account. This especially in the context where the workforce is increasingly mobile.

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.

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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Competitiveness—the engine that boosts economic growth and revives the economy

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Competitiveness is a concept that shows up in all aspects of human life, both at the micro level, in personal, social, and professional life, and at the macro level, linked to organizational and national competitiveness with long-term effects on global competitiveness. In this paper, we aim to address competitiveness in Romania in the current context, before and after the COVID-19 pandemic, highlighting its role in reviving the economy. While until the onset of the pandemic Romania's competitiveness performance was growing, more recently, because of the global health crisis, it dropped a few places, according to the Global Competitiveness Index report. In order to have a clear picture of the degree of competitiveness in Romania, we have presented a series of statistical data for the most relevant macroeconomic indicators for our study for the 2017–2022 timeframe: the global competitiveness index, the minimum wage, labor productivity, the evolution of real labor productivity per employed person, the economic growth rate, the unemployment rate, the inflation rate, the European innovation index, gross domestic expenditure on research and development, export of goods and services as a share of GDP, etc. The methodology used involves the use of quantitative techniques, performing an econometric analysis, and correlating how the most important macroeconomic indicators can influence the degree of competitiveness at both the national and international level. For the post-pandemic timeframe, the analysis switches focus, just as the economic reality did, looking at energy costs and energy use as determinants of competitiveness. Since notions like circular economy and sustainable development correlate being energy-efficient with being competitive, however, at the same time, the high cost of investments necessary for individual businesses and countries to switch from polluting energies to clean energies impedes or at the very least heavily impacts their ability to compete with entities that don't make that same switch, it becomes apparent that the energy market impacts competitiveness metrics. Competitiveness promotes valuable contributors and underpins performance at group and company level, and the effects from the micro level will propagate, with an emission effect, to the entire national economy with obvious implications at the international level, through real growth in macroeconomic indicators, increased labor productivity, increased economic performance (market share, export share, return on capital), raising living standards and economic and social wellbeing (life expectancy index, human development index, poverty rate), education (skills, knowledge, abilities, managerial and marketing skills, corporate culture), competitive potential

(innovation, R&D, promotion), and in raising the Global Competitiveness Index by focusing on factors of production, efficiency, and innovation, etc.

KEYWORDS

competitiveness, economic growth, energy crisis, medical crisis, labor market

1 Introduction

All individuals in an economy tackle competitiveness as a challenge, considering it an essential condition for efficiency and standing out in a certain market, be it local, national, or international. When viewed through the lens of competitiveness, Romania's economy is not in a favorable position compared to the economies of the other EU member states; however, when looking at statistical data for a longer timeframe, collected both at the national and at the European level, a case can be made that Romania has taken important steps in terms of improving its competitive environment and meeting some competitiveness index targets.

A focus on competitiveness among individuals, economic agents, nations, and economies is significant inasmuch as its comprehension and implementation, as opposed to a zero-sum game, creates only winners. By framing competitiveness as an individual pursuit, in which everyone strives to be effective at their job, gives their best according to their intellectual and professional skills and abilities, takes responsibility for their deeds and actions, engages in constructive and beneficial competition for all, promotes values, and sustains performance at the group and company level, these individual behaviors will spread, as a result of a spillover effect, to the entire economy, society, and world. This will be evidenced by an increase in real macroeconomic indicators, labor productivity, economic performance (market share, export share, return on investment), the standard of living and economic and social wellbeing (life expectancy index, human development index, poverty rate), education (skills, knowledge, abilities, managerial and marketing skills, corporate culture), and competitive potential (innovation, research-d), among others.

Competitiveness and economic growth are intimately intertwined, mutually reinforcing each other; therefore, increased competitiveness leads to increased economic growth, which in turn can increase competitiveness. Competitiveness is the engine of economic growth because it motivates businesses to boost their productivity, allocate resources to innovation, research, and development, and enhance the quality of their products. Competitiveness refers to the capacity of a country or company to generate goods and services that can compete on the global market, whereas economic growth refers to the increase in the quantity of goods and services produced over time. Competition between enterprises will, on the one hand, drive firms to produce more and better-quality items, which will benefit consumer economic agents, while on the other hand, it will generate larger profits, firms will grow their market share, and be able to attract more clients. The rise in turnover at the microeconomic level and the gross domestic product at the macroeconomic level will, over time, lead to an increase in investment, which will generate an increase in aggregate supply, resulting in a rise in employment and, consequently, a rise in the standard of living and social and economic welfare. Moreover, competitiveness is essential for attracting international investment and expanding exports, both of which can further drive economic growth. When a nation is competitive, it is more likely to attract foreign investment, which can provide enterprises with capital, technology, and knowledge to enhance their competitiveness and productivity. This can result in increasing exports, which can contribute to economic expansion. To increase economic growth, it would be beneficial to focus on competitiveness-enhancing measures, such as investments in education, infrastructure, innovation, and trade liberalization.

Competitiveness is a significant driving force for development and improving organizational performance, both at the macroeconomic level of analysis when researching topics related to a national economy's performance, and when the research is done at the microeconomic level, particularly when looking at individual companies, be they private, public, or joint. While for an individual microeconomic entity being competitive means striving to increase sales and define or consolidate brand awareness, thus increasing profits and becoming sustainable in the long run, this becomes the very engine that drives a national economy forward. Hence, a need for careful and detailed analysis of competitiveness and its interconnections with other essential, defining, and relevant elements specific to competitive economic activities, translated into research done both by scholars and by industry professionals.

Policymakers are also interested in promoting competitiveness, thus, a working group for competitiveness and economic growth has been established at the level of the Council of Europe. Its purpose is to prepare legislation and the principles for its application, to provide information about the European market and industry, and to serve as a forum for the exchange of information regarding national initiatives pertaining to competitiveness and economic growth, while also preparing the Competitiveness Council (Council of the EU, 2022).

2 Literature review

Competitiveness and economic growth are frequently viewed as closely intertwined ideas, however there are also arguments for a different view, namely, that competitiveness can occur at the expense of economic growth and *vice versa* (Porter, 1990; Reich, 1990; Krugman, 1994). In this regard, it is important to note the following: 1) some argue that competitiveness focuses on short-term gains, whereas economic growth requires long-term investments (innovation, education, and infrastructure), so policies that encourage competitiveness may boost productivity in the short term but may not lead to sustainable economic growth in the long term; 2) competitiveness can divert resources from other areas (social assistance, environmental protection, and public goods), and this can limit the resources available for investments that promote economic growth (education, research and development, as well as infrastructure); 3) competitiveness can have distributive effects, which means that benefits may not be shared equally among different groups in society, which can have negative effects on economic growth; and d) if a country's competitiveness is too high, it may not be able to attract foreign investment, and there may be a tradeoff between policies that promote domestic competitiveness and policies aiming at trade

balance and forgoing protectionism, and that tradeoff would have a negative impact on global economic growth.

There is no definition of competitiveness that is universally acknowledged in the specialized literature. Competitiveness is the capability of an individual or organization to gain competitive advantages over its rivals, and it can be applied to any field of endeavor. From an economic standpoint, competitiveness reflects the result of a series of interactions between internal and external factors, which yield benefits and competitive advantages to both companies and their own economies through the quantitative and qualitative increase of some indicators, such as productivity, efficiency, gross domestic product, real wages, wellbeing, and quality of life, etc. According to the World Economic Forum (WEF, 2017, p. 11), competitiveness is "the combination of institutions, policies, and factors that determine a country's competitiveness and productivity level". A relatively recent addition to the less than abundant body of research showing the impact that competitiveness has on macroeconomic performance, has been the Global Competitiveness Index, developed by the World Economic Forum, based on twelve pillars of competitiveness. The research team (Foster et al., 2017; Vîrjan, 2019; Lestari and Caroline, 2021) states that the defined concept of competitiveness, as measured by the GCI, includes static and dynamic competitiveness that can explain the potential for economic growth, while Sala-I-Martin et al. (2016) emphasizes the importance of adequately evaluating an economy's developmental stage in order to accurately set the scale for some of the components of GCI, grouping the twelve pillars into four subindexes.

Porter (1990), Porter and Ketels (2003) asserts that a country's competitiveness is contingent on the industry's capacity to be productive, innovative, and creative, as well as constantly adapted to the quantitative and qualitative demands of the market. He uses the term comparative advantage instead of competitiveness. Productivity, which is evaluated by the value of goods and services produced per unit of human capital and natural resources, is the true metric of competitiveness. A nation's productivity will enable it to maintain high salaries, a strong currency, attractive returns on capital, and a certain level of living.

Endeavouring to contribute to a substantiation of the elusive nature of competitiveness, Aiginger (2006), Aiginger and Vogel. (2015) differentiate between input and output competitiveness and develop indicators for both. Costs, structure, and capabilities (competitiveness drivers) as well as economic, social, and ecological performance are used to rank nations (performance pillars). Using econometrics and principal components, the individual drivers are used to explain outcome competitiveness. Providing a set of indicators to measure "low-road" and "high-road" competitiveness results in significant new policy findings. Defining competitiveness as a country's or nation's capacity to achieve objectives beyond GDP modifies the policy conclusions drawn from the pursuit of competitiveness. In comparison to "high-road strategies" based on skills, innovation, and supporting institutions, cost-cutting measures are inferior. For high-income nations, ecological ambition and social investment are not costs, but rather enablers of competitiveness.

Delgado et al. (2012) define fundamental competitiveness as the projected level of production per person of working age that is supported by a country's total business climate. Focusing on output per prospective worker, a larger measure of national productivity than output per existing worker, illustrates the dual importance of workforce participation and output per worker in shaping the quality of living of a country. Their theory emphasizes three broad and interdependent determinants of fundamental competitiveness: social infrastructure and political institutions, monetary and fiscal policy, and the microeconomic environment. The authors of this model estimate this framework utilizing different data sets encompassing over 130 nations throughout the period of 2001–2008 and numerous data sources and discover that each of the three drivers has a positive and significant effect on production per worker. Even after correcting for historical legacies, the microeconomic environment has a positive influence on prospective worker production. Within this framework, the paper proposes a new notion, global investment attractiveness, which is the relative cost of factor inputs to a country's competitiveness. In addition to providing valuable insight into the economic trajectory of certain nations, the research provides a unique way for estimating a theoretically based and empirically confirmed measure of national competitiveness.

Terzic (2021) explores the significance of competitiveness and innovation in stimulating economic growth in certain European countries, including Romania, and concludes that economic growth is influenced by competitiveness and innovation, who in turn are heavily reliant on macroeconomic stability, solid developed institutions, a strong financial system, an improving business environment, and ability to innovate.

Gama et al. (2020) try to establish a link between economic growth and competitiveness, based on data taken from the World Economic Forum (WEF, 2020) whereby the twelve pillars are grouped into three subindexes, namely, basic requirements, efficiency enhancers and innovation and sophistication factors; their model sets efficiency enhancers and innovation and sophistication factors as dependent on the evolution of basic requirements in previous periods, suggesting that an economy's level of activity is a function of the current and delayed growth rate of basic requirements. The study carried out for 105 countries highlights the fact that the level of economic activity of the analyzed countries is in a positive relationship with the competitiveness measures; it additionally concludes that the current and lagged rate of the basic requirements are the main determinants of a country's level of activity.

Research carried out on a sample of Member States in Central and Eastern Europe by Korez-Vide and Tominc (2016) explores and analyzes a country's competitiveness and entrepreneurship as determinants of economic growth. The analysis shows that economic growth, measured by GDP *per capita* growth rates, and a country's global competitiveness, measured by the growth rates of the World Economic Forum (WEF) Global Competitiveness Index, are positively related; however, no significant relationship was found between GDP *per capita* growth and the growth of quality of early-stage entrepreneurship indices, thus indicating that entrepreneurship promotes economic growth only as part of a wider favorable business environment.

A study setting out to explore the relationship between competitiveness and economic growth done for Romania's 42 counties (Simionescu, 2016), narrowed by the premise that the national competitiveness is not driven innovation and investments in human capital, makes an empirical assessment of the impact of occupation and unemployment in Romanian counties

on economic growth. The approach based on panel vector-autoregressive models (VAR panel) indicated a negative impact of the occupation and the activity rate in 42 counties in Romania on economic growth during 2006–2014; this finding is not only at odds with previous research (Iordan et al., 2014), but is also an apparent theoretical paradox, that real economic growth was achieved with high unemployment rates. The contradictory findings might be explained by issues in the labor market aggravated by the global economic crisis of 2008, such as higher unemployment rate, higher undeclared/underground employment, and potentially lower productivity of human capital due to both accelerated emigration process and skills erosion during the labor market adjustments made because of diminishing production.

Another interesting approach to the subject, originating from the reality of the great economic crisis of the first decade of the 21st century, is that of Cordero (2008), which looks at competitiveness, income distribution and economic growth in a relatively small economy. In keeping with the 1980s spirit of the post-Keynesian economic perspective, Cordero (2002) shows that for a small economy international competitiveness is a more relevant determinant of demand and effective growth, while also explaining a negative association between outward-oriented policies and income distribution in the long-run. The paper also advocates that this pattern can be broken with an institutional framework that encourages productivity growth when international competitiveness decreases, the model being able to generate endogenous growth.

An analysis focusing on competitiveness at a sector level, specifically tourism (Pablo-Romero et al., 2016) reviews theories related to competitiveness and the indicators used to measure it, and studies linking tourism and growth, with the aim of establishing the interconnections between both concepts. The study concludes that endowment with inherited tourism resources together with acquiring productive resources, and the conjunction between both, are the determinants of an economy's ability to produce and therefore to grow.

Three interrelated aspects are examined by da Cunha Resende and Torres, 2008: the National Innovation System, Trade Elasticities, and Economic Growth. Along the process, he discovers that disparities in the income elasticity of imports and exports between nations result in varying degrees of external growth limitations. Despite having undergone industrialization processes, numerous economies continue to encounter external growth restrictions. Using neo-Schumpeterian literature, the author wants to illustrate the causal linkages between the growth of a National Innovation System, the variations in the income elasticity of imports and exports, an economy's competitiveness, and its external vulnerability.

Zagoršeková et al. (2018) focuses on competitiveness at the national level and the impact of competitiveness on economic growth at the European level and finds significant differences in competitiveness among the member states of the European Union, according to the index of global competitiveness, published by the World Economic Forum. In the examined sample, the positive relationship between the level of competitiveness and economic growth was not confirmed. It is shown that economic competitiveness has long been one of the key political priorities of the European Union, which can stimulate economic growth by promoting digitization and individual and national welfare; thus, the EU can maintain its competitiveness due to a highly skilled and healthy workforce, strong social and economic security and minimizing inequality.

In a study carried out on a sample of 114 countries, the researchers (Kordalska and Olczyk, 2016) start their analysis from the widely accepted idea that the global competitiveness index is treated as a standard for measuring the competitiveness of countries, which is expected to be inextricably linked to economic growth, however, empirical analysis of this relationship are few and far between, and the economic literature is parsimonious when it comes to answering whether economic growth can be used to predict future global competitiveness or *vice versa*. The study assesses this relationship by means of a Granger causality test and confirms a strong unidirectional causality between the analyzed countries, i.e., GDP growth determines global competitiveness; but, somewhat surprisingly, the GCI fails to predict economic growth for most of the 114 countries analyzed, with the exception of a few large economies such as China, India, the United States and Russia.

Merdić and Hodžić (2022), analyzed how competitiveness impacts the exports of goods and services of European economies grouped in three subsets: CEFTA countries, the European Union and the European Monetary Union; their results show a positive and statistically significant impact of the Competitiveness Index (GCI) on the exports of European economies for EU and EMU economies, but the impact is missing in the case of CEFTA countries.

It is now widely accepted that innovation is one of the most important factors in the growth of a nation's economy, and it has been embraced as a primary instrument for increasing value and attaining a durable advantage over competitors. Based on that premise, de Miranda et al. (2021) carried out a this research the purpose of which was to get an understanding of the effect that global competitiveness has on the worldwide innovation of nations. A multiple linear regression analysis was used to assess certain indices of 133 different countries. According to the findings, the degree to which a country is competitive on the global stage has a considerable and beneficial effect on its inventive capacity. Education and training at higher levels were the competitiveness factors that had the most significant impact on the innovative capacity of countries.

Those findings were in line with a previous empirical study carried out by Dima et al. (2018), in a research that analyzed the Global Competitiveness Index (GCI) in relation to a number of different indicators connected to the knowledge economy: research and development (R&D) expenditure (as a percentage of gross domestic product), percentage of population with tertiary education, lifelong learning, GDP *per capita*, and debt to equity using the Pearson coefficient and panel-data regression models. The results brought to light the significant part that education and innovation play as key predictors of the level of economic convergence and competitiveness within the EU. According to the findings of the empirical study, two of the most significant factors that contribute to a nation's level of competitiveness are its level of educational outcomes and its level of innovation.

In a study evaluating the World Economic Forum's Global Competitiveness Index, Lall (2001) defines "competitiveness" in

economics as the ability and economic performance of a nation to sell and deliver products and services in a specific market relative to other nations in the same market. The World Economic Forum's "Global Competitiveness Index" ranks 137 countries based on their capacity to sustain equitable economic growth. The assessment of competitiveness utilized twelve indicators, including innovation, infrastructure, and macroeconomics. The relationship between innovation and the willingness to adopt new technologies has a significant influence in the nation's overall performance, economic resiliency, and robust labor market. The author identifies two main contemporary concerns, namely, the unregulated growth of capital markets and the continued expansion of private debt in developing nations. He observes that other developing nations, such as India, have excelled in innovation, but have been unable to capitalize on their progress due to the lack of a population and corporations willing to adopt new technologies. The author emphasizes that measuring the economy's competitiveness should incorporate factors such as the wide distribution of economic gains, environmental sustainability, and intergenerational equity for young people and future generations, thereby achieving a resilient economy and prosperity for all.

3 Analysis of competitiveness in Romania before and after the pandemic

3.1 Materials and methods

The methodology used involves the use of quantitative techniques, performing an econometric analysis, and correlating how the most important macroeconomic indicators can influence the degree of competitiveness at both national and international level.

While the crisis of 2008 left its mark on all activities in the economy, and, after 2 years of decreases and imbalances manifested both at the micro and macroeconomic level, a need for a relaunch of economic activity was apparent, so was Romania's engagement on the path to increase performance in terms of competitiveness during 2010–2018. This section of our paper focuses on descriptive statistics that highlight the global competitiveness index and several influencing factors, such as the minimum wage, labor productivity, the growth rate of per person real labor productivity, the employment rate, the economic growth rate, the unemployment rate, the inflation rate, the European innovation index, the gross expenditure on research and development, the export of goods and services as a share of GDP, etc.

Based on the literature regarding cost-driven competitiveness and Romania's uniquely high wage growth rate we also performed an econometric analysis to test our hypothesis that there is a positive correlation between the global competitiveness index (GCI) and the minimum wage (SM).

Before the pandemic crisis, competitiveness was influenced by a number of economic factors, including productivity, wages, export of goods and services, innovation and development index, and other factors. However, with the pandemic, the outbreak of war, and the energy crisis, we aimed to verify our hypothesis that the structure of competitiveness cannot be identical and determined by the same indicators, given the rise in energy prices and the onset of the energy crisis. Thus, in the econometric analysis, we used a panel data model using the econometric software Eviews 8. All variables were gathered from the Eurostat database, and we studied the competitiveness index for 2019, using the competitiveness index at the national level in 2018 as a control variable.

The GCI (national competitiveness index) was the dependent variable in a regression equation, whereas the other variables were independent: GCI(-1) the national competitiveness index from the preceding period; access to electricity (the population's access to electricity), IMPORTS TO GDP (the proportion of imports to GDP), PSI (the political stability index), and QUALITY OF ROADS (the infrastructure quality index).

3.2 Competitiveness in Romania during 2010–2018

When the World Economic Forum issued the Global Competitiveness Index 2017–2018 (WEF, 2018), Romania was placed number 68 out of 137 nations, with a Competitiveness Index of 4.3 on a scale from 1 to 7. This ranking was the outcome of the World Economic Forum weighing more than one hundred unique economic indicators (see Table 1). As compared to the result of the previous year, this one revealed Romania to have fallen six places, and 2 years previously to that, the country was ranked 53 and had a GCI of 4.32. Countries such as Bulgaria (ranked 49th), Estonia, the Czech Republic, Lithuania, Latvia, Poland, and Russia were all ranked higher than Romania. On the other hand, Switzerland and the United States of America tied for first place with an index of 5.9, followed by Singapore, the Netherlands, and Germany with an index of 5.7, followed by Hong Kong 7, the United Kingdom, Japan, and Finland with an index of 5.5. etc.

Out of the three subindexes of GCI, Romania's best performance was recorded for the subindex "Basic requirements", at 4.6, wherein the lowest scored pillars were the first and the second, Institutions and Infrastructure respectively (lack of highways, poor development of national roads and railways); managing director for Eastern Europe and the Caucasus (EEC) at the European Bank for Reconstruction and Development (EBRD) Matteo Patrone warned that "the Romanian infrastructure gap has become a serious obstacle to the convergence process and steps have to be taken" (Tudor, 2018). Within the "Efficiency Enhancers" sub-index, Romania's best performance is for the ninth pillar, Technological readiness, indicating the existence of IT specialists, then the 10th pillar, Market size, showing opportunities for potential investors, while the lowest scored pillar is the eighth, Financial market development, which points towards a lack of financial education both in schools and in the people's everyday life. The low scores for pillars in the third subindex, "Innovation and sophistication factors" are not surprising for Romania's emerging economy, where low investment in research-development -innovation makes it hard to innovate.

Pârvan (2018) noted that between 2010 and 2016 Romania had been the only European country to have decreasing performances regarding the capitalization of resources, so much so that by 2017 Romania's consumption of material resources per euro produced as measured by GDP was three times the European average. Moreover, it had been downgraded in other

TABLE 1 The global competitiveness index for Romania 2017–2018.

Basic requirements	Efficiency enhancers	Innovation and sophistication factors
Rank 72, score 4.6	Rank 58, score 4.3	Rank 107, Score 3.3
1st pillar: Institutions	5th pillar: Higher education and training	11th pillar: Business sophistication
Rank 86, score 3.7	Rank 70, score 4.4	Rank 116, score 3.5
2nd pillar: Infrastructure	6th pillar: Goods market efficiency	12th pillar: Innovation
Rank 83, score 3.8	Rank 92, score 4.1	Rank 96, score 3.1
3rd pillar: Macroeconomic environment	7th pillar: Labor market efficiency	
Rank 38, score 5.2	Rank 89, score 4.0	
4th pillar: Health and primary education	8th pillar: Financial market development	
Rank 92, score 5.5	Rank 88, score 3.7	
	9th pillar: Technological readiness	
	Rank 51, score 4.8	
	10th pillar: Market size	
	Rank 41, score 4.6	

Source: World Economic Forum, 2017, The Global Competitiveness Index 2017–2018.

international rankings as well: dropped five places in a global ranking regarding the ability to develop and retain talents, dropped two places in the Global Tourism Competitiveness Report, Romania's capital city, Bucharest, dropped sixteen positions in the Global Urban Competitiveness Report, ranking at 188th place out of 200 cities, and consistently ranking 34th out of 35 countries evaluated for the Euro Health Consumer Index.

Labor productivity, in addition to the growth rate of the real productivity of labor per employed person, is an essential indicator for determining a country's level of competitiveness. Throughout the years 2010–2016, Romania had the highest rate of real labor productivity growth per employed person, propelling the country to the top spot among Western European nations. However, after that point, the rate began to decline and by 2018 it had reached 3.9%.

When looking at the relationship between the evolution of labor productivity, the minimum wage, and the total labor cost it becomes apparent that wage increases were not based on the increase in labor productivity, as the growth rate of the total labor costs exceeded the rate of labor productivity growth; the wage increases, particularly in the public sector (healthcare +31.76%, education +19.85%, public administration and defense +12.07% etc.) (INS, 2019) were not found to be correlated with the increase in labor productivity; double-digit salary increases are uncommon, particularly in developing nations; the rise in labor expenses was likely to be reflected in the pricing of products and services and damage the buying power of consumers, thus causing an increase in both the inflation rate and the general price index.

The minimum wage grew annually, reaching 2,080 lei at the start of 2019. While its absolute value was the lowest compared to other EU Member States, its percentage rise of 195% over the preceding decade was the greatest. This increase had both positive and negative effects; increasing the minimum wage strains the business environment, particularly for small and medium-sized enterprises, promotes the growth of the shadow economy through the use of unregistered and thus untaxed workers, particularly those whose output is below the minimum wage, and raises labor costs for businesses, causing them to lay off some workers, all of which have implications for declining competitiveness.

The increase in the minimum wage has had a positive impact on disposable income and it has reduced income inequality (Gini Coefficient dropped from 37.4% in 2015 to and 34.7 in APERC (2016) and further to 33.1 in 2017—European Commission, 2019), is likely to have positively impacted long-term growth potential, by stimulating consumption and aggregate demand and thus short-run economic growth; it also had a positive impact on the employment of young people on the labor market (according to statistical data the increase of the minimum wage by 1% led to an increase of the employment rate among young people by about 2%). Over the course of the previous 10 years, Romania had relied on the "low-cost" workforce, and had it continued in that race to the bottom it was likely to lose, since at any point production could be relocated to countries where labor is much cheaper, the tax system and fiscal duties are lax enough to encourage foreign investment, and where there is more macroeconomic stability.

Romania's legal framework for public policy to monitor and prop up national competitiveness was established by Government Decree no. 775/2015, later amended by GD no 640/2018; they render the National Competitiveness Strategy (NSC, 2015) 2015–2020 and identify ten economically competitive sectors: tourism and ecotourism, textiles and leather, wood and furniture, creative industries, automotive and components, information and communication technology, food and beverage processing, health and pharmaceuticals, energy and environment management, bio-economy, biopharmaceuticals and biotechnologies. These sectors can be supplemented by other economic sectors identified in complementary strategic documents such as the Governmental Strategy for SME Growth and the Improvement of the Romanian

TABLE 2 Macroeconomic indicators with impact on competitiveness.

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Labor productivity	100	102.8	110.3	115.2	118.2	124.3	131.8	137.5	142.7
Evolution of the real labor productivity per employed person	5.3	5.4	5.4	5.6	5.4	5.2	6.0	4.3	3.9
Minimum wage	670	700	750	800	850	1,050	1,250	1,450	1900
Inflation rate (%)	6.1	5.8	3.3	4	1.1	−0.6	−1.5	1.3	4.6
Unemployment rate (%)	7.3	7.4	7	7.3	6.7	4.2	3.8	3.3	2.9
Economic growth rate (%)	−1.1	2.3	0.6	3.5	3.1	3.9	4.8	6.9	4.2
European Innovation Index	47	47	40	40	32	30	32	33	-
Gross domestic expenditure for R&D (% of GDP) and EU-28	0.45	0.49	0.48	0.38	0.38	0.48	0.48	-	-
	1.83	1.87	1.91	1.92	1.94	1.95	1.93	-	-
Exports of goods and services (% of GDP) and EU-28	32.6	37	37.5	39.7	41.2	41.0	41.3	41.4	-
	38.4	41.1	42.3	42.4	42.8	43.4	43.2	44.6	-

Source: Eurostat, Word Bank, European Innovation Scoreboard, INS, 2010–2018.

Business Environment, which identifies sectors likely to bolster the competitiveness of SMEs are identified, and the Strategy for the National Defense Industry which emphasizes the need to enhance competitiveness of the national defense industry at regional, European and NATO levels.

To increase the capacity of firms' research and innovation economy, the government has implemented a number of policy measures, including providing SMEs with high-quality services designed to facilitate innovation, supporting knowledge-based start-ups, developing and launching new products, and developing incentives for collaboration between large businesses, SMEs, and universities. Table 2 shows that the European innovation index for Romania decreased by 14 points between 2010 and 2017, categorizing it as a "modest innovator" and the nation with the lowest percentage of SMEs offering innovations in goods (65% below the EU average), placing it 25th among the EU-28.

In the analyzed pre-COVID period, Romania was similarly towards the bottom of the rankings (26th out of 28 member states) in terms of R&D spending; for instance, in 2016 gross domestic R&D expenditures amounted for 0.48% of GDP, which was around four times lower than the EU-28 average (see Table 2). Although in most Member States, R&D funding were allocated to the commercial sector, with the exception of Estonia, Greece, Cyprus, Latvia, and Lithuania, which channeled money to higher education, almost half (43%) of R&D expenditure in Romania was conducted by the government (Dogaru, 2015; Cao et al., 2022).

The export of goods and services is also a relevant economic indicator when examining competitiveness; accordingly, an additional public policy document could have been construed as part of the national competitiveness legal framework, namely, a strategy meant to improve Romania's export performance, the National Export Strategy (NES, 2014) for 2014–2020, targeting four strategic perspectives: the development approach (investment, clusters and regional development); the sectoral approach (facilities, supply adjustment, external promotion, branding); the beneficiaries/exporters approach (customer segmentation, quality, innovation and R & D, skills, financing); the institutional approach (strengthening the institutional ability to expand exports and ensure NES management). The statistical data in Table 2 doesn't show a

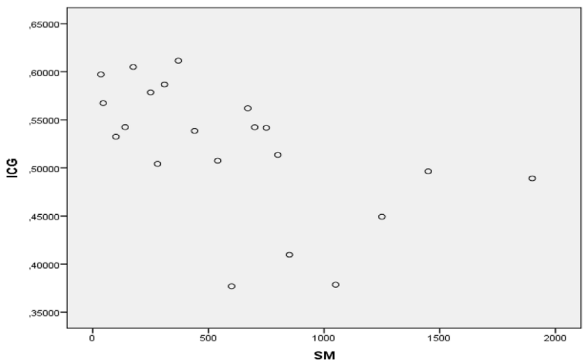

FIGURE 1
ICG = f(SM).

Mean	Std. Deviation	N
.5205133	.06893806	21
605.00	491.805	21

		ICG	SM
Pearson Correlation	ICG	1,000	−.547
	SM	−.547	1.000
Sig. (1-tailed)	ICG		.005
	SM	.005	
N	ICG	21	.21
	SM	21	21

Model	R	R square	Adjusted R square	Std. Error of the estimate	Durbin-watson
1	.547[a]	.300	.263	.05919697	1.508

Model	Sum of squares	df	Mean square	F	Sig. (b)
Regression	.028	1	.028	8.124	.010
Residual	.067	19	.004		
Total	.095	20			

a. Dependent Variable: ICG.
b. Predictors: (Constant), SM.

significant impact of the strategy to improving exports, an increase of only 0.02 percentage points of exports' share of GDP from the strategy's inception, in 2014, until the end of the investigated pre-pandemic timeframe; moreover, for that same period, the gap between values for Romania and average values for EU-28 actually increased from 1.6 percentage points to 3.2 percentage points.

3.3 Econometric analysis - the influence of the minimum wage on the economy on the competitiveness of Romania, before the pandemic

We have considered an econometric model whereby the Global Competitiveness Index is the dependent variable, abbreviated as ICG, and the independent variable is the minimum wage, abbreviated as SM; we used statistical data collected for 2010–2018 timeframe and discussed in the previous section of the paper.

The findings of data processing indicate a somewhat strong negative correlation between the two variables. At a significance level of 5%, the linear correlation coefficient Person is statistically significant (Figure 1).

The determination coefficient is 0.300, which indicates that 30% of the variation in the dependent variable (ICG) is explained by the change in the independent variable, namely, the effect of the minimum wage on the economy. At a significance level of 5%, the Durbin Watson test indicates that the non-self-correlation error assumption is verified.

Model Summary[b]

ANOVA[a]

Coefficients[a]

The model parameters are statistically significant at a significance level of 5%. The value of parameter B1 is 0.567; this is the ICG modification that is not caused by the independent variable shown earlier. The value of parameter B2 is −0.0000767, which indicates that the ICG will drop by an average of 0.0000767 for every 1 RON rise in the minimum wage.

At a 5% level of significance, the above two graphs (Histogram of Standardized Residuals–Figure 2, and PP Plot of Standardized Residuals–Figure 3) and the Kolmogorov Smirnov Test verify the normality of errors hypothesis (standardized errors were used). There is an inverse median correlation between ICG and SM, such that 30% of the variance in ICG can be attributed to the impact of SM; hence, the model parameters are statistically significant at the 5% significance level.

3.4 Competitiveness before and after the pandemic crisis

The medical crisis caused by the COVID-19 pandemic has caused an economic crisis that has generated other macroeconomic imbalances, overlapping with the energy crisis, geopolitical crisis, ecological crisis, and social crisis. The price increases for most market goods, particularly energy prices and the price of natural gas and other non-renewable and non-recoverable resources, are an important source of concern and impact the behavior and actions of all entities involved in economic activity, be they individuals, businesses, national public agencies, governments, and international organizations alike. While during the pandemic businesses generally faced losses, decreased revenues, and high costs, the post-pandemic recovery came with another shock, namely, higher energy bills, generating a negative impact on the entire economy at the national, European, and international level. After wholesale energy prices fell sharply in 2019, in 2020 the trend suddenly reversed, and prices increased by 200% compared to 2019, due to the high demand for gas worldwide, but also the decrease in the volume of natural gas from Russia. The increase in gas and electricity prices has impacted industrial activity and SMEs, affecting production and revenues, national and international supply chains, energy-intensive industries, and the transport and mobility sector, which

Model	Unstandardized coefficients		Standardized coefficients	t	Sig	95,0% confidence interval for B	
	B	Std. Error	Beta			Lower bound	Upper bound
(Constant)	.567	.021		27.275	.000	.523	.610
SM	- 0.0000767	.000	−.547	−2.850	.010	.000	.000

a. Dependent Variable: ICG.

One-Sample Kolmogorov-Smirnov Test.

		Standardized residual
N		21
Normal Parameters[a,b]	Mean	0E-7
	Std. Deviation	.97467943
	Absolute	.169
Most Extreme Differences	Positive	.103
	Negative	−.169
Kolmogorov-Smirnov Z		.773
Asymp. Sig. (2-tailed)		.588

a. Test distribution is Normal.
b. Calculated from data.

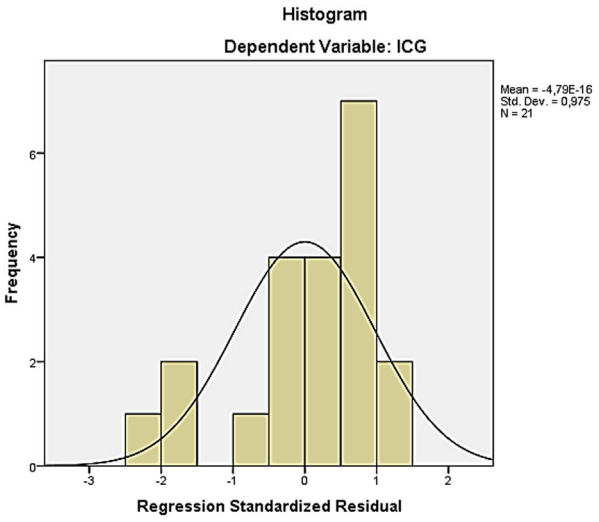

FIGURE 2
Standardized Residual Histogram.

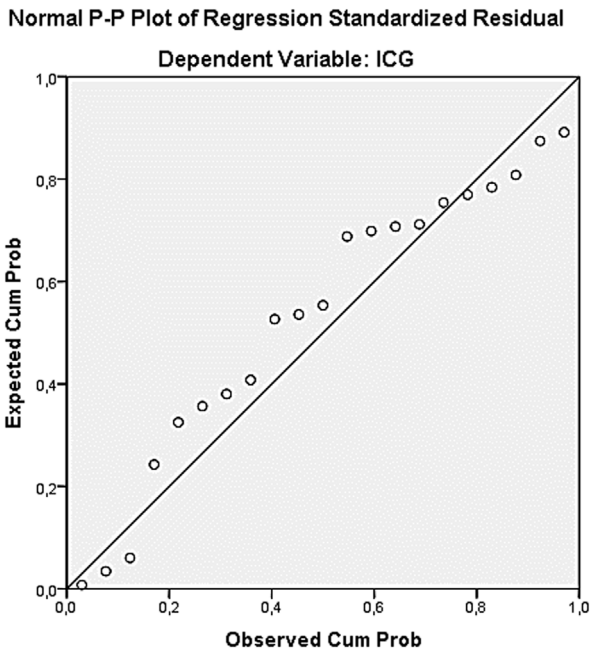

FIGURE 3
Standardized Residue Plot Chart.

in turn has caused a supply decrease of raw materials and components for various industries, especially the food industry.

With energy being an input in all types of economic activity, when high production costs force businesses to curtail their scope and lower their activity level, or, in worst case scenarios, when average total cost exceeds the price, to exit the market altogether, and also when rising prices and inflation also impact the buyers, not just the businesses, this creates a new context that underpins a perspective change for competitiveness, not just in terms of measuring it but also in terms of understanding what drives it.

The energy crisis, caused by multiple influencing factors, has thus influenced competitiveness, not only at a microeconomic level for individual actors on specific markets but also at the macroeconomic level for the economy as a whole—aspects regarding the availability of, access to, and eco-efficiency of energy all factor into businesses' decision-making and their ability to prevail over their competitors.

Notions like circular economy and sustainable development, promoted by the European Union through encouraging policies meant to bolster them, correlate being energy-efficient with being competitive, regardless of whether that efficiency regards use of classic sources (coal, oil, and gas) that are considered polluting through carbon dioxide emissions, and having an important impact on climate change, as well as use of those sources considered clean, such as nuclear, solar, wind, or water energy.

While currently the European Union states are affected not only by the economic reverberations of economic stagnation and decline due to the COVID-19 pandemic but also by the military conflict between the Russian Federation and Ukraine, they have also embraced legislative changes to limit the use of classic energy resources such as coal, oil, and gas and promote replacing them with less polluting energy sources, considered clean energies. Proponents of these measures view the transition to a clean, green, ecologically based economy as the best insurance policy against energy shocks and production and consumption crises. However, the high cost of investments necessary for individual businesses and countries to switch from polluting energies to clean energies impedes or at the very least heavily impacts their ability to compete with entities not bound to make that same switch, thus making it apparent that the energy market impacts competitiveness metrics.

Companies that, following the onset of the pandemic, invested in acquiring and using production facilities based on clean energy now have a competitive advantage over traditional ones in terms of access to energy and avoiding environmental sanctions related to pollution. However, this competitive edge came at the cost of high outlays of money spent on new green energy systems such as energy capture systems with photovoltaic panels, investments in micro-hydro-plants, windmills, micro-nuclear plants, etc., investments with very high initial costs that had a fulminant start and then a similarly rapid interruption due to a lack of long-term strategy and policies appropriate to the context and infrastructure.

10.3389/fenvs.2023.1130173

TABLE 3 The global competitiveness report 2018–2019, Romania.

2018/2019 component index	Score	Rank/140	Score	Rank/141
1st pillar: Institutions	58.1	46	58.1	52
2nd pillar: Infrastructure	71.2	55	71.7	55
3rd pillar: ICT adoption	67.1	36	72.0	32
4th pillar: Macroeconomic stability	89.2	53	89.7	56
5th pillar: Health	79.8	72	77.2	83
6th pillar: Skills	61.8	69	62.5	72
7th pillar: Product market	57.3	56	55.4	64
8th pillar: Labor market	60.7	56	61.6	57
9th pillar: Financial system	51.9	101	57.0	86
10th pillar: Market size	64.7	41	65.2	41
11th pillar: Business dynamism	60.1	64	59.7	72
12th pillar: Innovation capability	39.6	57	42.3	55

Source: WEF, the global competitiveness report, 2019 (pp.478–481), 2018 (pp.493–495).

Transitioning from an economy based on the intensive use of classic fuels with high carbon dioxide emissions to one based on alternative, less polluting sources requires considering the transition costs, which can be high and have a major influence on competitiveness. The correlation between competitiveness and energy availability, and the mutual influences of these two variables, are likely to be different depending on the economic sector analyzed: the extractive industry, the processing industry, the energy industry, transport, agriculture, and tourism. For each of these sectors, the competitive advantage based on energy availability (either in terms of type or in terms of costs) will come at different costs and will confer diverging benefits.

For both Romania and other European countries, the rural eco-tourism and rural entrepreneurship sector is a good example of how to improve competitiveness by investing in clean energy and using local material and intangible resources. This sector has the potential to add a lot of value to the economy, but it only makes up a small part of GDP right now. Soare et al. (2017) point out the fact that in this sector, access to electricity becomes a particularly important element in evaluating competitiveness and consequently eventuating as a determinant of economic development and sustainable economic development.

According to the latest Global Competitiveness Report published by the World Economic Forum, Romania's GCI ranking improved from 52nd place in 2018 to 51st place in 2019 (see Table 3) (WEF, 2018; WEF, 2019; WEF, 2020).

Even though the use of ICT, the size of the market, higher education, and vocational training could be seen as strengths for Romania, the country still has problems in areas like infrastructure, innovation, and institutions. In terms of transportation and energy infrastructure, Romania is still behind other EU countries. To make the country more competitive, we need to improve the quality of roads, railways, ports, and airports. Regarding innovation, Romania lags behind in terms of spending on research and development and patent applications, which limits its ability to create and market new products and services. The institutional environment is inefficient, opaque, and prone to corruption, and a lack of trust in public institutions and the judicial system has discouraged investment and limited economic growth.

Romania needs to invest in infrastructure, encourage innovation, strengthen its institutional environment, and improve communication between the government, the private sector, and civil society in order to find and fix the country's competitiveness gaps. This will make the country more competitive and improve its GCI ranking.

3.5 Econometric analysis—the influence of the price of energy, the import of goods and services in GDP, the quality of the infrastructure and the index of political stability on competitiveness

In the econometric study, we used a panel data model using the econometric software Eviews 8 as our primary tool. All of the variables were taken from the Eurostat database, and the competitiveness index is being evaluated for the year 2019, with the competitiveness index at the national level in 2018 serving as a control variable. We used a regression equation, in which the GCI (national competitiveness index) is the dependent variable, while the other variables are the determinant variables: GCI(-1), which stands for the national competitiveness index in the preceding period; ACCESS TO ELECTRICITY, which refers to the population's access to electricity; IMPORTS TO GDP, which stands for the proportion of imports in GDP; PSI, which stands for the political stability index; and QUALITY OF ROADS (the infrastructure quality index).

The regression equation is the following:

$$\begin{aligned}\mathbf{GCI_{it}} = {} & \mathbf{C(1)} + \mathbf{C(2)}^{*}\mathbf{GCI(-1)_{i(t-1)}} \\ & + \mathbf{C(3)}^{*}\mathbf{ACCESS\ TO\ ELECTRICITY_{it}} \\ & + \mathbf{C(4)}^{*}\mathbf{IMPORTS\ TO\ GDP_{it}} + \mathbf{C(5)}^{*}\mathbf{PSI_{it}} \\ & + \mathbf{C(6)}^{*}\mathbf{QUALITY\ OF\ ROADS_{it}} + \mathbf{u_{it}}\end{aligned}$$

TABLE 4 Results of econometric analysis.

Variable	Coefficient	Std. Error	t-Statistic	Prob
COMPETITIVENESS(-1)	0.940255	0.013908	67.60332	0.0000
ACCESS TO ELECTRICITY	0.007727	0.005056	1.528253	0.1290
IMPORTS to GDP	−0.000331	0.003152	−0.104986	0.9166
PSI	0.243116	0.132000	1.841782	0.0679
QUALITY of ROADS	0.462839	0.118607	3.902287	0.0002
C	1.592161	0.569348	2.796463	0.0060
R-squared	0.994560	Mean dependent var		61.02500
Adjusted R-squared	0.994344	S.D. dependent var		12.40483
S.E. of regression	0.932911	Akaike info criterion		2.743375
Sum squared resid	109.6606	Schwarz criterion		2.874411
Log likelihood	−175.0627	Hannan-Quinn criter		2.796622
F-statistic	4607.168	Durbin-Watson stat		0.000000
Prob(F-statistic)	0.000000			

Respectively

$$\mathbf{GCI_{it}} = \mathbf{1,592} + \mathbf{0.940}^{*}\mathbf{GCI}\,(-1)_{\mathbf{i(t-1)}} + \mathbf{0.007}^{*}\mathbf{ACCESS\ TO\ ELECTRICITY_{it}} + \mathbf{0.0003}^{*}\mathbf{IMPORTS\ TO\ GDP_{it}} + \mathbf{0.243PSI_{it}} + \mathbf{0.462}^{*}\mathbf{QUALITY\ OF\ ROADS_{it}} + \mathbf{u_{it}}$$

where i = country (Romania); t = year t (2005–2021) = year ($t = \overline{1,16}$); $\mathbf{u_{it}}$ represents random error for country i, year t

C(1) stands for the model's constant, often known as the intercept. C(2), C(3), C(4), C(5), and C(6) are the elasticity coefficients of the dependent variable, which show how it responds to changes in the independent variables. All of the coefficients of the independent variables that were considered are statistically significant, which indicates that these variables are representative and have power to explain the variation in the dependent variable. Our findings, which are based on the panel model, show that the model is valid, coherent, and autoregressive during the time period that was examined, after the necessary adjustments were made in the Eviews 8 program. In addition, it was found that the model was valid after the adjustments were made Table 4.

As hypothesized, econometric analysis reveals that the competitiveness index has a very prominent self-regressive pattern. Consequently, it is observable that the lag value of this indicator is statistically significant at a significance level of 1%. The competitive index of the current year is favorably impacted by the competitiveness index of the previous year, and the fact that Romania achieved a ranking in the GCI in 2019.

The index of political stability has a direct proportionate and statistically significant association with the degree of competitive agency at a degree of relevance of 1%, thus a rise of 1% of this level indicates an estimated increase of 0.24 percentage points in the competitiveness rate. The degree of political stability influences the degree of competitiveness since economic actors will gain trust in public authorities and be inspired to invest, diversify and improve their production structure, produce profit, and clearly boost global competition as a result.

The infrastructure quality index is another independent variable that has a positive and statistically significant link with the degree of competitiveness, such that a 1% rise in this index leads in an estimated 0.46 percentage point gain in competitiveness. This variable is significant because it may positively affect economic development by boosting productivity, decreasing transportation costs, attracting foreign investments, streamlining the economic circuit overall, and improving the standard of living.

Our regression model reveals that there is no clear empirical evidence linking access to electricity with competitiveness. The relationship is positive, but the correlation coefficient is weak (0.007), indicating that, to the degree that competitiveness is dependent on fuel price and access to power, the impacts of the energy crisis or the increase in the price of power have long-term implications on economic activity, but our timescale is quite brief. As for the link between competitiveness and the import to GDP ratio, it is negative, and the correlation coefficient is extremely weak, indicating that there is no clear empirical evidence between the two variables.

All coefficients are statistically representative at a confidence level of approximately 95%, The R-squared coefficient is 99.4%, indicating that the model is valid/representative and that the selected variables explain the behavior of the independent variable, the Durbin-Watson test statistic (Durbin - Watson stat) is 0.00—indicating that there is no autocorrelation of the errors, and the F-statistic coefficient suggests that the selected variables are significantly associated with the independent variable and the chosen model is valid.

4 Discussion

We came up with the regression model based on the current economic and political state of the world, including the recovery from the pandemic, the war between Russia and Ukraine, and the

energy crisis. We also took into account the fact that the degree of competitiveness is affected not only by economic factors but also by a number of other factors that can affect competitiveness and economic growth. Because of this, our model also includes non-economic factors like the index of political stability. Even if the correlation between these independent factors and the dependent variable is not very high, the association is positive and statistically significant at the 1% level of significance.

We expected a stronger relationship between the degree of competitiveness and access to electricity because the price of electricity went up a lot during the pandemic. The relationship is positive, but the correlation is very weak, so we can't say that the energy crisis had a big effect on the degree of competitiveness. It is to be expected that a sudden increase in fixed and material costs will negatively impact companies' profits, both due to cost increases and potential revenue decreases, thus jeopardizing future production of goods and services and future economic growth. Investments in infrastructure, education, and innovation are prerequisites for achieving a certain level of competitiveness and economic development, which in turn secures a particular level of economic and social wellbeing.

The analysis of the composite indices is based on a small amount of data, so even though the correlation factors are statistically significant, the direction is only one-way. A multidirectional relationship would be better to get more complete results and a better idea of how the constructs interact with each other.

It is also worth mentioning that regression models can't prove cause and effect and that there may be other factors that affect both the ICG score and the GDP growth rate, such as political stability, natural resources, and demographic factors. Because of this, regression analysis should be combined with other types of empirical and qualitative analysis to give a fuller picture of how competitiveness and economic growth are related.

5 Conclusion

The economic activity is changing and transforming continuously, since its end result, the final product, is supposed to address new, developing, and evolving needs manifested as market demand originating from a diverse and transforming consumer base. This principle has been underpinning industrial development with increasing output levels and fueling consumerism, engaging rising resource consumption, and generating waste and pollution. When trying to place competitiveness within this framing, it emerges as a type of inertia that creates a feeling of wellbeing and enthusiasm and that pushes us to create interesting and useful things for everyone by using renewable, reusable, and recoverable resources that do not pollute the environment and bring us joy and wellbeing. More does not mean better; more beautiful does not mean better quality; more comfortable does not translate to wellbeing; economic growth does not mean economic development; and the results of competition and economic activity should be looked at while balancing the results and satisfaction for the actors involved, producers as well as consumers, with a concern to not harm and protect the environment, the standard of living, health, quality of life, and life expectancy.

In practice, the competitiveness of a nation is not an end in itself, but a means to an end; some approaches to the theories of competitiveness, such as the theory of competitive advantages, the theory of price competitiveness, the perspective of management strategies, and so on, are all valid; however, the ultimate goal must be to increase the real income of citizens and improve their quality of live; this is because the competitiveness of a nation is not an end in itself, but a means to an end.

The current study shows how the world is changing and how people need to be able to adapt on the spot to meet new challenges. For the timeframe preceding the outbreak of the pandemic crisis, we analyzed the relationship between competitiveness and a number of macroeconomic indicators, such as real GDP *per capita*, labor productivity, the minimum wage per economy, and exports of goods and services, and found a positive correlation between the global index of competitiveness and real GDP *per capita*, labor productivity, and exports of goods and services, and an inverse relationship with the minimum wage per economy, which was expected in the context of that period (2010–2018), a period of economic recovery after the financial crisis of 2008. In the current context, in a reality defined by the aftermath of a medical crisis caused by the COVID-19 virus and being in the midst of both a geopolitical and an energy crisis, a different approach to competitiveness from a different perspective becomes necessary. One cannot talk about competitiveness without considering investments in infrastructure (roads, bridges, railways, air, sea, and rivers), in research-development and innovation, in green technologies, in cheap energy by replacing classic energy sources with renewable energy, in human capital (i.e., preparing, acquiring skills, and constant improvement by the labor force), in the stimulation of local, regional, and national potential by harnessing even resources such as traditions and customs, in investing in projects to find alternative resources to replace the natural and exhaustible ones, etc. We are looking at a paradigm shift where the focus is, on the one hand, on developing green technologies, such as wind energy and solar panels, on alternative sourcing of resources derived from processing primary and natural ones, and, on the other hand, on education, on learning to manage our resources more efficiently, to recycle, to reuse, to recover intermediate goods, to make compost, to lower the environmental as well as material costs of consumption, to let go of the compulsion to stock up on perishable goods, and to take care of the natural, social, and community environment.

While cooperation rather than competition would be required for all responsible actors (public authorities, individuals, and private entities operating either at the national or international level) to pursue a cleaner and healthier environment, we cannot discard that plausible risk reviews that take into account real energy prices, input prices (material and labor costs), and local, regional, and national financial and economic climates will reveal different types of influences on competitiveness and an economic entity's adequacy to national and international markets.

The findings of the research indicate that the connection between economic growth and competitiveness can shift in response to a wide variety of factors, including those that are economic and non-economic, social and environmental, medical (such as a pandemic), political, geopolitical, and macroeconomic, and the list could go on. What nations need to do is direct their attention and investments toward those policies that promote the expansion of culture and education, guarantee political stability,

modernize and develop infrastructure, invest in research and development, innovate products and services that do not pollute the environment, have employment policies that are sound, and guarantee wellbeing and quality of life.

The degree to which political unrest, violence, or disruption of operations and production, distribution, and marketing activities can be expected is a significant factor in determining the level of competitiveness in an economy. This is because political stability creates an environment in which economic agents can operate without the threat of political unrest, violence, or disruption. A politically stable environment, by which we mean the stability of the government, the efficacy of law enforcement, the low incidence of terrorism, and the low probability of violent demonstrations, helps to attract domestic and foreign investments and increases the population's confidence in justice and public administration. This, in turn, determines the increase in the degree to which economic agents become involved in the context of economic growth and development.

Countries with a high index of political stability tend to be more competitive than those with a lower index. This is because political stability can improve the environment for doing business and create opportunities to produce more and better goods domestically, both of which can translate into greater competitiveness on the global market. Countries with a lower index of political stability tend to have a lower standard of living overall.

Building up a nation's economy and making it more competitive requires significant investment in the country's infrastructure. Many countries have paid increased attention to investments in the modernization and development of infrastructure (railways, highways, ports, airports, communication networks) to increase their competitiveness, which has led to the creation of new jobs and an increase in the quality of life of citizens. Excellent infrastructure enhances productivity, decreases transport costs, enables the movement of products and services across regions and nations, and gives improved access to public transit systems, drinking water, and power. Inadequate infrastructure, which results in greater costs for transport and logistics, may be a barrier to attracting foreign investment and makes products and services less competitive on international markets. Bad infrastructure also contributes to increased expenses for moving people and goods.

Because the relationship between economic growth and competitiveness is intricate and nuanced, and depends on a number of factors (such as the particular policies and institutions that are in place, the level of economic development, and the distributive effects of different policies), it is essential to adopt an all-encompassing strategy that takes into account not only economic growth and competitiveness, but also other social and environmental goals. The Global Competitiveness Index (GCI) for Romania has increased over the last several years, but the country still has opportunity for more development.

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.

Author contributions

DV designed the research plan, analyzed the data, and wrote Sections 1, 3-5 of the manuscript. AC co-wrote Section 2 of the manuscript, analyzed the data, and revised the manuscript. CP collected and analyzed the data and revised the manuscript. AM co-wrote Sections 2, 4 of the manuscript, analyzed the data, and revised the manuscript. MS-P, DH, and CB analyzed the data and revised the manuscript. All authors have checked the final version of the manuscript 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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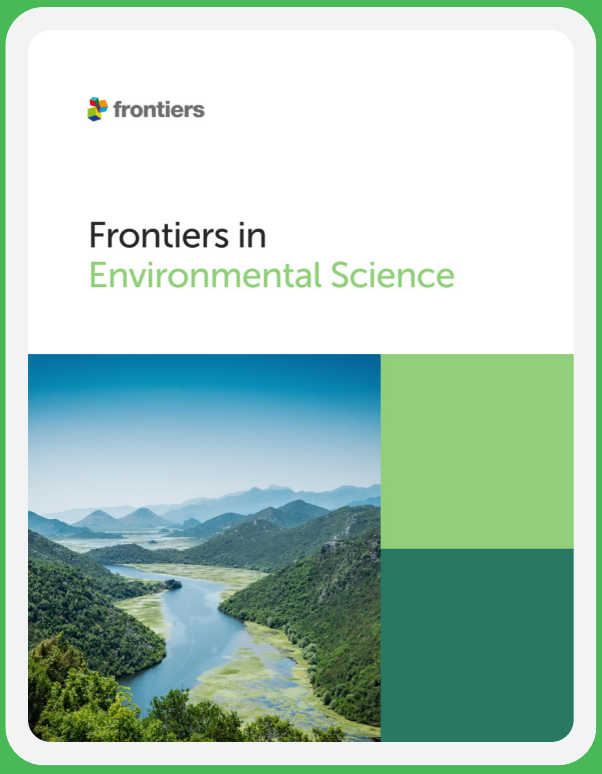

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