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Can climate-related information disclosures strengthen green innovation capacity? Firm-level evidence using textual analysis

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ABSTRACT

This study presents novel insights on modelling the implications of voluntary climate-related information disclosure on corporate green innovation (GI) in China. Based on a constructed dataset of 13,664 firm-year observations between 2014 and 2020, we quantify climate-related disclosures under the *Task Force on Climate-Related Financial Disclosures* framework using computerized text analysis. Our findings show that climate-related information disclosure substantially bolsters corporate green innovation after addressing endogeneity concerns. However, the promoting effects vary drastically across industry attributes, ownership structure, and environmental regulations. Further channel analysis demonstrates that "greenwashing" behaviours and financial constraints adversely moderate the nexus between climate-related information disclosure and green innovation of firms, while digital finance positively moderates it. Overall, this study enriches the literature and offers practical implications for firms engaging in the green innovation process more effectively under a more transparent environment-related disclosure system.

1. Introduction

Climate change has been recognized as a major and urgent global challenge facing mankind (García-Sánchez et al., 2023; Wright & Nyberg, 2017; Wu et al., 2024). Due to the heavy consumption of fossil fuels in the industry and transportation sectors and the degradation of carbon sinks, it is predicted that the world is likely to reach a 1.5 °C (2.7 °F) increase in global temperature in the next twenty years (2021–2040) (IPCC, 2021). Increasingly, the heightened climate risk leads to firms' growing awareness of environmental practices and informs the need for green technologies to reduce fossil fuel consumption (Li & Lu, 2023; Tian et al., 2023). The increased environmental pressures and firms' engagement in corporate social responsibility (CSR) have promoted scholarly discussion about the environmental disclosure of firms and their performance consequences. Bai et al. (2023) also highlight that firms exhibit heterogeneous propensities in disclosing information regarding their environmental practices, which are affected by factors such as the resources and capability of firms, regional economic development needs, or changes in government policies.

Climate-related information disclosure is defined as firms reporting their risk management processes and practices in responding to climate change (García-Sánchez et al., 2023). Due to the growing discussion on coping with global warming, recent studies highlight the public's need for climate-related information to evaluate the environmental performance of firms and, therefore, make decisions

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on supporting or denying their green innovation (GI) practices. One stream of research utilizes the signalling theory to argue that by closing climate-related information, firms can convey positive market signals to investors and obtain financial support for the development of new environmental technologies (Friske et al., 2023; Mervelskemper & Streit, 2017; Wedari et al., 2021). Researchers identify that such disclosures can minimize agency conflicts and positively impact firms' stock market valuation (Tao, 2024a; 2024b). Another stream of research considers the pressure from multiple stakeholders (Guenther et al., 2016; Li et al., 2018; Xing et al., 2021), suggesting that climate-related information disclosure enables addressing stakeholders' environmental concerns, thereby enhancing the legitimacy of their new investments and environmental projects. Despite the research efforts, the literature on climate-related information disclosure and firms' GI outcomes is limited.

Moreover, the public's trust in firms' environmental disclosure is regarded as a critical factor that determines the effectiveness of the firms' efforts. Climate-related information disclosure by firms operating in clean and high-polluting industries may yield significantly different results on GI. For instance, due to high-polluting firms rely heavily on natural resources for their business activities and their lack of incentives to invest in R&D (Fan et al., 2020; Lin et al., 2021; Shao et al., 2020), the quality and effectiveness of their climate-related information disclosure may be lower than those of clean firms. State-owned firms (SOEs) usually play significant roles in China's economic development and environmental governance (Chang et al., 2015; Fan et al., 2020; Yu et al., 2022). Compared with non-SOEs, SOEs are under tremendous institutional pressure for information disclosure, and these firms can quickly obtain financial support and tax reductions for their environmental innovation practices (Fan et al., 2020). However, we still know little about whether the climate-related information disclosure and GI relationship vary across SOEs and non-SOEs. In addition, it is noticeable that firms are guided by environmental regulations in disclosing information and investing in new technologies (Du, 2015; Wedari et al., 2021; Xing et al., 2021). Under different thresholds of environmental regulations, the relationship between climate-related information disclosure and GI may change. However, the current research on the relationship is insufficient, leading to our limited understanding of how firms can contribute to addressing climate risk through improving transparency of their environmental activities and developing green technologies and GI. In this study, we ask the following research questions: *How does climate-related information disclosure affect firms' GI? What factors contribute to the heterogeneity in the relationship?*

This study addresses the research gaps by adopting a mixed-method approach, including textual analysis and regressions based on a comprehensive dataset comprising climate-related information disclosed by Chinese firms between 2014 and 2020. We further investigate the external contingencies that can moderate the relationship. We consider the influence of greenwashing behaviour (GW) of firms, which refers to the efforts of firms to cloak environmental misconduct by overly claiming their environmental contributions (Delmas & Burbano, 2021; Du et al., 2015). GW may affect the public's trust in information disclosure, thereby revising the disclosure-GI relationship. We acknowledge the importance of growing digitalization and the impact of digital finance (DF), defined as the digitalization of the financial industries, entailing electronic transactions based on digital financial products and services (Gomber et al., 2017). Considering that DF changes firms' available information and financing channels, we assume that DF can positively moderate the relationship. We also examine the financial constraints (FC) firms face in their environmental practices, which affect the motivation for firms to disclose information about their climate-related efforts and their ability to engage in GI (Song et al., 2021; Zhang et al., 2021).

Our contribution to the literature is threefold. First, this study extends the existing literature on environmental disclosure by using textual analysis to investigate the climate-related information disclosure of firms. Our analysis elucidates the impact of such disclosure on GI, enriching the research on environmental disclosure by emphasizing the context of climate risk. Second, we compare corporate industry, ownership characteristics, and different stringency of environmental relationships in examining the relationship between climate-related information disclosure and GI. Our findings reveal the heterogeneity of the relationship, adding novel insights to the research on environmental disclosure and sustainable development. Third, considering the rapid digitalization and financial inclusion (Gomber et al., 2017; Goldfarb & Tucker, 2019; Liu et al., 2021), we examine the moderating effects of digital finance and financial constraints on firms' disclosure and GI. We also consider the potentially misleading information firms disclose and test the moderating effect of greenwashing. By doing so, we provide a theoretical basis for analysing internal and external mechanisms that contribute to firms' green behaviours and innovation. We also respond to recent calls for examining the greenwashing in climate-related information disclosure, the impact of digital finance, and the role of government policies in firms' environmental innovation practices (Bai et al., 2023; Hu et al., 2021; Jiang et al., 2022; Wedari et al., 2021). From a practical aspect, our findings provide significant policy implications, helping to identify new possibilities for addressing climate risk pressures.

This study proceeds in the following order. Section 2 recaps the literature review. Section 3 presents the methodological framework. Section 4 reports the empirical findings. Section 5 provides further analyses. Section 6 is the conclusions.

2. Literature review and research hypotheses

2.1. Climate-related information disclosure and GI

In literature, several studies employed the signalling theory to explain the climate-related information disclosure of firms, suggesting that such disclosures enable investors and analysts to understand the coverage of firm operations and their efforts in coping with climate change (Friske et al., 2023; García-Sánchez et al., 2023; Huang, 2022). According to the signalling theory, asymmetric information increases the likelihood of agency conflicts, which hinders firms from improving their decision-making efficiency. By voluntarily disclosing strategic decisions in responding to climate-related issues, firms can send a positive signal to the market and explain their ideas about promoting sustainable development (Mervelskemper & Streit, 2017). Unlike traditional financial reports, climate-related information disclosure increases the transparency of the firms' environmental practices (Friske et al., 2023;

Mervelskemper & Streit, 2017). Such information disclosure can also lead to higher creditworthiness and enable firms to obtain financial support for their GI projects, as investors and analysts can improve business forecasting with more climate-related information.

Some studies also draw from the stakeholder theory to highlight the need for climate-related information disclosure in addressing the stakeholders' concerns over their environmental practices and investment plans (Guenther et al., 2016; Li et al., 2018; Xing et al., 2021). Since GI is characterized as developing new ways to address environmental problems (Li et al., 2022; Takalo & Tooranloo, 2021), firms are required to convince their internal and external stakeholders not only about the effectiveness of the new technologies but also about the positive externalities that GI can bring to reduce environmental costs. With the need to address stakeholders' concerns, climate-related information disclosure has become essential for firms to enhance their environmental legitimacy and promote GI (Guenther et al., 2016; Li et al., 2018). The green credit policy in China targets financial support to eco-friendly firms (Xing et al., 2021; Zhang et al., 2022). Without disclosing sufficient environmental information and illustrating the degree of eco-friendliness, firms are less likely to convince banks, the critical stakeholders controlling the loans. Therefore, climate-related information disclosure acts as a toolkit for firms to communicate with essential stakeholders and obtain support for their new technological investments, thus resulting in better GI. Therefore, we propose the following.

Hypothesis 1 (H1). The intrinsic nexus between climate-related information disclosure and corporate GI is positive.

2.2. Industry attributes, ownership characteristics, and environmental regulations

2.2.1. Industry attributes: clean and high-polluting firms

Compared with firms from cleaner industries, firms from high-polluting industries face tremendous legitimacy pressure and higher costs for environmental investments (Li et al., 2018; Wang & Zhang, 2021; Wu et al., 2021). In literature, research shows that upstream cleaner firms often develop emission reduction technologies and new techniques before being sold to downstream high-polluting industries (Shao et al., 2020). Due to the high dependence on natural resources for production, high-polluting firms often show fewer incentives and lower ability to invest in clean technology R&D (Shao et al., 2020). Therefore, despite being forced to disclose information about environmental practices, high-polluting firms tend to refrain from investing in new technologies for GI, as the R&D efforts in these industries are regarded as a waste of resources (Shao et al., 2020). Even though high-polluting firms are encouraged by stakeholders to invest in clean technologies, their climate-related information disclosure may not be likely to gain trust (Fan et al., 2020; Lin et al., 2021). This is because news media regularly report how much environmental damage those high-polluting activities trigger. In addition, some high-polluting firms are likely to disclose climate-related or low-quality information selectively (Lin et al., 2021), detrimental to trust and support for their GI.

The Chinese government introduced an Integrated Reform Plan in 2015 to promote ecological progress and urge firms to disclose environmental information (Fan et al., 2020). Since firms should disclose their contributions to coping with environmental issues and their emission and environmental violations, those heavy polluters face higher pollution abatement expenditures (Ahmad et al., 2019). This results in them spending more effort on pollution treatments, thereby being less likely to concentrate on GI investments. In addition, despite the Chinese government offering financial support to firms' environmental practices (Fan et al., 2020; Xing et al., 2021), high-polluting firms will find it challenging to access green credits. Those firms that receive green credits may exhibit good environmental performance and are not high-polluting firms (Hu et al., 2021). Therefore, we propose Hypothesis 2a as follows.

Hypothesis 2a (H2a). High-polluting firms are less likely to gain better GI in their climate-related information disclosure than cleaner firms.

2.2.2. Ownership characteristics: SOEs and non-SOEs

In China, the differences between SOEs and non-SOEs in environmental practices have been emphasized in previous efforts (Chang et al., 2015; Shahab et al., 2019; Tang et al., 2020; Zhu et al., 2016), indicating that the ownership structure of firms will lead to their environmental disclosure behaviour and GI outcomes varying. Among existing analyses, SOEs are featured by large firm size, rich funding support, state credit guarantee, and greater access to high-tech resources (Chang et al., 2015; Fan et al., 2020; Yu et al., 2022). The political connections of SOEs allow them to receive preferential treatment, such as paying lower environmental levies, accessing better terms from bank loans, and facing lower capital costs with low tax rates (Maung et al., 2016). In addition, SOEs have the advantage of attracting talent and high-quality human resources that can help them plan for climate-related strategies and develop green technologies. However, compared to SOEs, non-SOEs are subject to highly competitive pressures in GI (Maung et al., 2016), and their climate-related information disclosure may not be adequate due to a lack of trust and support from the investors and governments.

Chinese governments often promote the importance of climate-related information disclosure and other CSR requirements, beginning from those with state ownership (Fan et al., 2020). With growing stress from governments, SOEs, compared with non-SOEs, are more likely to follow policy guidelines to engage in improving GI and be given more incentives to cope with climate change (Fan et al., 2020). Under the incentives governments provide, SOEs are willing to undertake climate-related information disclosure practices in greater breadth and depth, which can help them meet public expectations and better demonstrate their capability for GI. Unsurprisingly, SOEs tend to disclose more information about environmental responsibility than non-SOEs, which aims to improve their public image as they are exposed more to public scrutiny (Chang et al., 2015; Fan et al., 2020). In line with the logic, we propose.

Hypothesis 2b (H2b). SOEs will likely maintain good relationships with key stakeholders, showing a more positive connection

between climate-related information disclosure and GI.

2.2.3. The degree of environmental regulations

Research on the relationship between environment and GI highlights that firms are affected by market mechanisms and subjected to environmental regulations (Huang et al., 2022; Peters & Romi, 2013; Shao et al., 2020). Hence, from a regulatory perspective, different stringencies in environmental regulations may lead firms to exhibit varying GI performance after disclosing climate-related information. Under different thresholds of regulations, firms' propensity to engage in GI will change due to the differences in innovation compensation and policy compliance costs (Huang et al., 2022; Wedari et al., 2021). In China, to tackle the pressing climate risk and promote sustainable development, the governments at all levels have made remarkable efforts to motivate firms to develop green technologies and engage in GI. However, under different institutional arrangements, governments in various cities and provinces impose different environmental regulation standards on firms, leading firms to present heterogeneous GI attributes and patterns after disclosing climate-related information (Huang et al., 2022). This indicates that governments' environmental regulations guide firms' behaviours and GI.

Strict environmental regulation may lead to a more positive nexus between climate-related information disclosure and GI. Following the literature on environmental regulation, coping with climate change challenges requires governments to provide more guidance and regulate firms' behaviour (Ding, Appolloni, & Shahzad, 2022; Dirckinck-Holmfeld, 2015). Firms often react proactively when there is tighter government regulation and face penalties for poor environmental performance (Ding et al., 2022; Shi et al., 2021). Indeed, government regulations may reduce the likelihood that firms will disclose irrelevant or insufficient climate-related information, which can assist firms in better communicating with necessary stakeholders to improve energy efficiency (Dirckinck-Holmfeld, 2015). The strict government regulations will also prompt firms to monitor their climate-related efforts and reconsider whether changes are necessary considering the regulator's agenda (Ding et al., 2022; Reid & Toffel, 2009). In this vein, government regulation helps firms convey credible signals to the stakeholders regarding climate-related information disclosure (Reid & Toffel, 2009), thereby acting more positively towards better GI outcomes. Hence, we propose the following hypothesis.

Hypothesis 2c (H2c). The promoting effects of climate-related information disclosure on corporate GI are more salient when firms face tighter environmental regulation.

2.3. The moderating effect of greenwashing behavior (GW)

Although global warming and stakeholders' concerns promote firms to disclose climate-related information and improve GI, it is noticeable that firms may engage in GW behavior under pressure from stakeholders (Delmas & Burbano, 2011; Wedari et al., 2021; Xing et al., 2021). Providing misleading disclosure offers an easier way for firms to improve their environmental reputation rather than investing in GI or changing business operations for better outcomes (Wedari et al., 2021). Research shows that because inferior environmental performers face more significant social pressures to disclose more information about their environmental activities, these firms are more likely to engage in GW practices (Wedari et al., 2021). Hence, some firms are not voluntarily disclosing their environmental practices but are simply utilizing GW to selectively disclose part of the climate-related information, preventing stakeholders' evaluation of their environmental performance.

If GW occurs, firms consider the benefits of disclosing climate-related information, such as maintaining legitimacy, improving their image, and diverting public attention from their environmental pollution (Delmas & Burbano, 2011; Wedari et al., 2021). Since investors and financial institutes rely heavily on corporate reports and advertisements, GW betrays their trust and may lead to adverse market reactions (Du, 2015). Without trust, the abovementioned effects of climate-related information disclosure will collapse, endangering the public's confidence in the firms' GI technologies, services, or products. Xing et al. (2021) argue that firms will be less likely to obtain loans if their environmental disclosures are misleading, as financial institutes are reluctant to grant loans to these greenwashers. Du (2015) utilizes a sample of China's listed firms and advocates that exposure to environmental wrongdoings of firms will decrease their stock market performance. Significantly, when the public or news media disclose their GW behaviors, firms' reputations will be perpetually damaged. Therefore, we propose the following hypothesis.

Hypothesis 3a (H3a). GW negatively moderates the nexus between climate-risk disclosure and GI.

2.4. The moderating effect of digital finance (DF)

With the rapid advancement of digital platforms, recent works on environmental management started to examine the impact of digital finance on firms' environmental engagement and innovation (Ren et al., 2023; Wang et al., 2022). On the one hand, DF allows firms to save financing costs and the effort to obtain critical information for their environmental management. Research shows that DF can improve the transparency of firms' governance and the quality of their information disclosure (Ren et al., 2023). Because the financial institutes can better evaluate firms' disclosed climate-related information more effectively through the DF systems, they can accelerate the financing process and allow firms to enhance their environmental management and GI promptly (Mu et al., 2023; Ren et al., 2023). The DF platforms also enable stakeholders to comprehend the purposes of climate-related information disclosure of firms, alleviate trust-related concerns, and moderate the detrimental implications of information asymmetry on their GI.

On the other hand, DF is inclusive in promoting capital and equity allocation, thereby providing additional support to firms' environmental innovation (Jiang et al., 2022). In China, the development of DF is found to have a positive impact on reducing carbon emissions and promoting firms to leverage the disclosure of climate-related information for better environmental engagement. For

instance, Wang et al. (2022) find that DF brings social benefits and helps address environmental problems in 284 prefecture-level cities in China. Liu et al. (2021) examine the impact of DF on China's economic growth and find that DF has lowered the thresholds for firms to access various kinds of financial services, boosting the firm's expansion and product innovation. Studies also find that DF can boost firms' enthusiasm for discovering more opportunities for GI, as the more capital and support they can obtain, the greater likelihood they will increase investments to R&D and GI for improving environmental performance (Jiang et al., 2022; Ren et al., 2023). Nambisan et al. (2019) suggest that digital transformation and DF affect firms' green technological innovation because powerful digital technologies open new opportunities for firms' value capturing and value creation. Given DF's potential advantages, we propose.

Hypothesis 3b (H3b). DF positively moderates the nexus between climate-related information disclosure and GI.

2.5. The moderating effect of financial constraints (FC)

Research on firms' environmental practices and GIs emphasizes the critical impact of financial constraints (FC), which designates markets providing limited financial resources (Cuerva et al., 2014). Xie et al. (2019) suggest that the resource-based view, which highlights the firm's internal resources and capabilities, can examine firms' competitive advantages and green product innovation. Gupta and Barua (2017) also emphasize that FC is detrimental to firms' ability in green operations. Firms must commit significant financial resources to facilitate GI in introducing new technologies and environmental programs. Despite climate-related information disclosure enabling firms to communicate with stakeholders and gain legitimacy for their GI investments, firms will have the capacity to innovate and to active new relationships with other vital stakeholders, such as firms that provide logistics services, suppliers, and public administration (Noci & Verganti, 1999). Notably, GI requires firms to explore new ways of coping with environmental issues and meeting the various stakeholders' needs. However, due to a lack of financial resources, firms are less likely to strategically invest at the suppliers' end to seek reliable and diversified resources for green operations (Gupta & Barua, 2017).

Moreover, FC reduces the firms' ability to manage uninterrupted operations and disruptions, as the lack of operational and financial slack leads to the firm's lack of flexibility in management (Gupta & Barua, 2017; Hendricks, Singhal, & Zhang, 2009). They have fewer options to switch their plans after disruptions, making their climate-related information disclosure less effective in promoting GI. In addition, research shows that financial instruments can provide a guide for firms to upgrade their production activities to an energy-saving mode, which are essential performance assessment mechanisms that guide GI (Irfan et al., 2022; Song et al., 2021; Zhang et al., 2021). Firms rely on financial instruments and capital support to transform their traditional energy projects into environmentally friendly projects (Zhang et al., 2021). For instance, Zhang (2022) suggest that capital flows from financial institutions to firms could create a signal to the market, helping firms gain more support from society and guiding them to invest more in environmentally friendly projects. Song et al. (2021) also argue that addressing the FC dilemma and promoting financial institutions to support sustainable development is essential, and the Chinese government has devoted more attention to removing financial barriers for environmental protection. Hence, FC creates obstacles for firms to take action to cope with climate-related issues that they have disclosed, leading to lower GI. Based on the above, we propose.

Hypothesis 3c (H3c). FC negatively moderates the relationship between climate-related information disclosure and GI.

2.6. Literature gaps

Despite the growing research attention on firms' environmental disclosure and performance (Ahmad et al., 2019; Fan et al., 2020), existing studies focus on examining the firms' disclosure of ESG (environmental, social, and corporate governance) information but have not considered climate-related information disclosure that is critical for coping with the pressing global climate change issues. Furthermore, although some studies emphasize the drivers and essential mechanisms of GI (Bai et al., 2023; Huang et al., 2022; Tian et al., 2023), less is known about whether climate-related information disclosure could increase or decrease GI outcomes. This study aims to fill the research gaps by investigating the nexus between climate-related information disclosure and GI.

Considering that many studies compare the different environmental practices in clean and high-polluting industries (Fan et al., 2020; Lin et al., 2021), between SOEs and non-SOEs (Maung et al., 2016; Shahab et al., 2019), and under different stringency of regulations (Dirckinck-Holmfeld, 2015; Shao et al., 2020), we aim to validate the heterogeneity of the nexus across various industries, ownership characteristics, and regulatory pressures. We also acknowledge that even though several studies have discussed the impact of GW in environmental management (Du, 2015; Wedari et al., 2021), researchers rarely incorporate firms' GW intentions that could change their GI outcomes after climate-related information disclosure. The extant literature also devotes less attention to considering the moderating effect of DF and FC on firms' disclosure behaviour and their GI outcomes. Therefore, by addressing the gaps, this study will advance our knowledge about GI and coping with the increasing global climate risk.

3. Methodology

3.1. Model formulation

Our primary analysis is grounded in a two-way fixed effects regression model. In particular, the baseline model is given as follows:

$$GI_{it} = \beta_0 + \beta_1 CIDS_{it} + \chi' X_{k,it} + \nu_j + \phi_h + \mu_t + \varepsilon_{it} \quad (1)$$

where GI_{it} represents the GI index for firm i at year t; $CIDS_{it}$ regulates the composite ESG score generated using the textual analysis technique corresponding to each firm; $X_{k,it}$ implies the selected firm-level characteristic variables utilized to rule out confounding impacts on firm-level GI performance; χ' is the response coefficients of $X_{k,it}$; ν_j, ϕ_h, and μ_t are province-, industry-, and year-fixed effects, respectively; ε_{it} is an error term; others regulate the relevant response parameters. Note that we do not control for firm fixed effects as our panel is unbalanced. In other words, our panel consists of multiple cross-sectional settings, e.g., pooled panel.

3.2. Selection of indicators

This study utilizes the logarithmic green patent granted to represent firm-level GI performance for the following reasons. In particular, we reorganize the importance of integration development between green technological advances and GI by measuring green outcomes (Wei & Zhang, 2020). On the one hand, green patent data has been extensively applied to gauge GI outputs (Yan et al., 2020). On the other hand, it is also helpful in ascertaining the efforts made by firms in terms of environmental protection. Moreover, past pieces have underpinned the importance of GI in strengthening firms' competitiveness, restructuring production modules, and promoting sustained economic growth (Fernando et al., 2019; Sun et al., 2022).

Our practice's primary core explanatory variable is climate-related information disclosure. Extant research primarily captures firms' environmental endeavours through ESG (Environmental, Social, and Governance) composite scores. In China, firms' ESG rankings are obtained from official ESG assessment organizations, yet the related allocation criteria vary considerably. Unlike previous trials, our study measures the firm-level climate-related information disclosure performance by referring to Engle et al. (2020).

Step 1. We first construct a training sample of Chinese firms to avoid the possible effects of lexical applications in the disclosed annual reports of each firm. To build the training sample, we need first to identify the supporters of the Task Force on Climate-Related Financial Disclosure (TCFD), which formally published its recommendations for climate-related financial disclosure in 2017 and plans to help firms provide information to support market transparency and more informed capital allocation. Among other things, we scrutinize companies willing to participate in the TCFD framework as a training sample. Note that our training sample involves only a small number of firms; also, hypothesis testing relies heavily on out-of-sample performance, so there is no overfitting issue. Moreover, the training sample differs from the final sample in that the training sample is only utilized to construct a comprehensive lexicon on climate change. In addition, since annual reports are the most basic information channel for firms to disclose environment-related information, we use the yearly reports in the training sample to build a climate-related thesaurus.
Step 2. This step extracts climate-related information and then cleans up the untidy information. For example, we use Python to extract corporate annual reports from the WIND database according to the climate-relevant information of the TCFD framework. Specifically, the TCFD introduces four dimensions: Governance, Strategy, Risk Management, and Metrics and Objectives. Each dimension also describes detailed disclosure recommendations. For example, the governance dimension under the TCFD framework suggests 1) describing the board's oversight of climate-related risks and opportunities and 2) describing management's role in assessing and managing climate-related risks and opportunities. As a result, training samples can be obtained objectively. After extracting the relevant keywords, we cleaned up all obtained information for a tidy format by dropping stop words and punctuations, stemming documents, and removing space (Gentzkow et al., 2019). For instance, some stopping words, such as "the" and "we," are excluded from the main text. The steaming process means that we uniformly build feature forms and reduce feature dimensions for identifications; meanwhile, words are transformed into their fundamental stemmer – for example, "advancement," "advancing," and "advances" are simplified into "advance."
Step 3. The cleaned climate change texts are labelled with words of length n, called n-grams. These n-gram words are aggregated and counted over the training sample for each firm at different years to construct a numeric vector. These words and their frequencies are termed a climate-related thesaurus.
Step 4. The annual reports issued by the firms in the final sample are parsed into text documents for text cleaning. Similarly, to construct the climate-related information disclosure, the text in each document is sanitized by removing stop words and punctuation and removing stemming and whitespace. These cleaned text documents are assembled into a climate change corpus. Next, we identify specific terms to determine whether the annual report is likely to contain any climate-related information, including "*climate change*," "*climate risk*," "*climate opportunity*," "*carbon emissions*," "*greenhouse gas emissions*," and "*greenhouse gases*," as these terms occur most frequently in phrase collocations with "carbon" or "carbon footprints." Companies that never used these terms in their reports were deemed not to have disclosed any climate-related information.
Step 5. We adopt the term frequency (TF)-inverse document frequency (IDF) to measure the text informativeness with the following formula:

$$TF - IDF = TF * IDF = f_{tf} * \log\left(\frac{N}{n_t}\right) \tag{2}$$

Eq. (2) implies that high-frequency words that occur in almost all texts will be assigned a lower TF-IDF score because of a low IDF score. Similarly, rare words appearing in a document will be given a lower TF-IDF score due to a low TF score, so both rare and common words are penalized when determining TF-IDF (Gentzkow et al., 2019; Hansen et al., 2017). However, a term can have a high TF-IDF score when it occurs many times in a minimal number of documents. Given this, we must calculate the TF-IDF score of each climate-related vocabulary to evaluate the informativeness of these terms in the entire sample. Lastly, the climate-related information disclosure index at the firm level is obtained using a similarity score determined by a cosine function (Ding et al., 2023).

$$Similarity = Cosine\left(TF-IDF_{climate-related\ information}, TF-IDF_{firm,i}\right) = \frac{\left(TF-IDF_{climate-related\ information,j}\right) * \left(TF-IDF_{firm,i,j}\right)}{\left|TF-IDF_{climate-related\ information,j}\right| * \left|TF-IDF_{firm,i,j}\right|} \quad (3)$$

where $TF-IDF_{climate-related\ information,j}$ represents the TF-IDF score of term j in climate-related information; $TF-IDF_{firm,i,j}$ regulates the TF-IDF score of term j in the i-th firm's yearly report; $similarity \in [0,1]$. As a result, we can calculate four sources under the TCFD framework. In particular, we treat each dimension equally essential, and subsequently, the firm-level climate-related information disclosure score can be generated using CIDS $= 0.25 *$ (Governance + Strategy + Risk Management + Metrics and Targets).

$X_{k,it}$ in Eq. (1) includes a set of control variables. Specifically, cash flow is represented by multiplying the firm's net profit by total assets; firm size is defined by the logarithm of the total number of employees; firm age is gauged by the logarithm of the firm's duration in the market, leverage ratio is quantified by total firms' leverage divided by the total assets; Tobin's Q is measured by the firm's market capitalization divided by asset replacement cost, and equity concentration is represented by the sum of the top ten shareholders' ownership ratio.

3.3. Research data

This study aims to evaluate the effects of climate-related information disclosure on firms' GI performance using a yearly public dataset from 2014 to 2020. We extract the raw data about firm-level characteristic indicators from the China Stock Market and Accounting Research (CSMAR) database, which covers almost all publicly listed firms on the Shenzhen and Shanghai stock exchanges. As noted previously, the firm-level CIDS composite score is computed based on the textual analysis technique, and the relevant data is sourced from the WIND database. Additionally, we drop several unique firms: 1) S&T, 2) financial firms, and 3) excluding firms with debt higher than their total assets. Furthermore, all values are winsorized at 1% and 99% to rule out potential impacts induced by outliers. Lastly, the extrapolated approach is introduced to complete variables with missing values. Table 1 outlines the statistical descriptions of each indicator. In particular, the average GI index is 0.325, with a standard deviation of 0.707. This observation implies that the overall GI performance in our test sample is relatively low, and the GI index also presents substantial variations among observations.

Table 2 shows that the firm-level CIDS index is relatively stable with a relatively small standard deviation. Interestingly, four dimensions exhibited heterogeneous features regarding the sample average. Additionally, the strategy and metrics & objectives indices have the highest sample average compared to other sub-indicators. As depicted in Fig. 1, strategy mainly encompasses three essential items. The highest sample average delivers that more than 50% of firms attain the mean threshold of CIDS regarding strategy specification. Further, the metrics & objectives dimension mainly responds to the strategy dimension, such as the exact measures addressing climate-related risks against the stipulated targets.

Table 2 displays the correlation matrix and the associated VIF test. First, the correlation coefficients between regressors are relatively low, lower than 0.5. Second, we also check multicollinearity within the panel. Intuitively, the VIF value of each regressor is low. In the meantime, the average VIF is 1.18, suggesting no possible multicollinearity concerns in our analysis.

4. Empirical results

4.1. Fundamental regression results

Table 3 presents the benchmark regression outcomes. Column (1) gives the findings without controlling any firm-level characteristic variables; in contrast, we only check the correlation between climate-related information disclosure and firm-level GI. Our primary focus, the climate-related information disclosure index, generates pronounced effects on firms' GI, with the regression coefficient of 0.7640, passing the 1% significance level test. Subsequently, we incorporate the selected control variables and observe the variations of the CIDS estimates, as presented in columns (2)–(7). Fortunately, the corresponding estimates do not vary substantially

Table 1
Statistical description.

Variable	Obs.	Mean	Std. Dev.	Min	p1	p99	Max
GI	13664	0.325	0.707	0.000	0.000	3.178	6.006
CIDS	13664	0.450	0.076	0.000	0.014	0.206	0.796
Governance	13664	0.374	0.131	0.000	0.017	0.385	0.985
Strategy	13664	0.590	0.125	0.000	0.011	0.191	0.996
Risk Management	13664	0.234	0.136	0.000	0.007	0.289	0.998
Metrics and Objectives	13664	0.605	0.146	0.000	0.005	0.140	0.980
Cash flow	13664	0.036	0.063	−0.358	−0.199	0.186	0.230
Leverage ratio	13664	0.163	0.149	0.000	0.000	0.549	0.620
Tobin's Q	13664	2.194	1.616	0.692	0.872	8.32	56.813
Firm size	13664	7.825	1.180	3.555	5.384	10.968	12.722
Firm age	13664	2.046	0.866	0.000	0.000	3.258	3.401
Equity concentration	13664	0.566	0.155	0.088	0.235	0.913	1.000

Table 2
Correlation matrix and VIF test.

	CIDS	*Clash flow*	*Leverage ratio*	*Tobin's Q*	*Firm size*	*Firm age*	*Equity concentration*	VIF	1/VIF
CIDS	1.000							1.01	0.994
Cash flow	0.005	1.000						1.16	0.859
Leverage ratio	0.017**	−0.294***	1.000					1.28	0.780
Tobin's Q	−0.000	0.081***	−0.223***	1.000				1.13	0.884
Firm size	0.053***	0.001	0.320***	−0.281***	1.000			1.36	0.736
Firm age	0.060***	−0.241***	0.296***	−0.029***	0.372***	1.000		1.31	0.764
Equity concentration	0.016*	0.031***	−0.066***	0.002	−0.067***	−0.139***	1.000	1.02	0.979

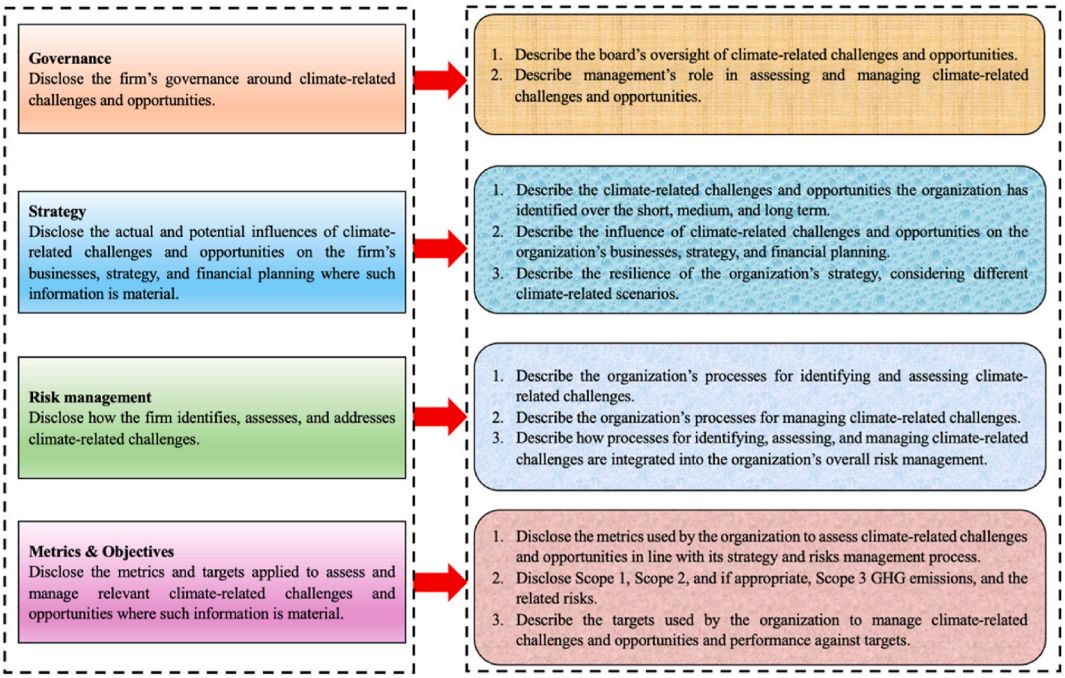

Fig. 1. Climate-related information disclosure framework.

after considering multiple fixed effects, with the main interval running from 0.7450 to 0.9078. Specifically, after including all control variables, the central estimate of CIDS is 0.7571, which is salient and positive at the 1% significance level. Conclusively, climate-related information disclosure persistently promotes firms' GI.

The estimates of the firm-level characteristic variables align with expectations. Among them, the cash flow and firm size coefficients are positive, coinciding with Yuan & Wen (2018), indicating that firms with a high cash share and large-size firms function better in GI. The leverage ratio, Tobin's Q, firm age, and equity concentration adversely affect corporate GI. Yet, the corresponding effects of leverage ratio and equity concentration are insignificant; in contrast, Tobin's Q and firm age significantly depress caproate GI. This observation aligns with the seminal works of Kong et al. (2021) and Wang et al. (2021), who also drew the same conclusions. On the one hand, since, as confirmed in the innovation literature, firms that make inventions do not always benefit from them (Nelson, 1959), the difference between societal needs and private profitability (Aghion & Howitt, 1992) is almost inherent in incomplete contracts (Grossman & Hart, 1986). The negative correlation between green effort and market value may thus simply reflect a political will to subsidize what the market perceives as more socially desirable than privately profitable.

4.2. Robustness tests

The fundamental results suggest a positive correlation between climate-related information disclosure and corporate GI. However, additional tests are necessary to test the feasibility of the previous findings.

First, unobservable factors may influence firms' climate-related information disclosure, resulting in potential endogeneity due to self-selection bias. Therefore, we apply a Heckman two-stage regression technique to tackle the above issue. Specifically, we designate the top 30% of firms in the climate-related information disclosure index as the experimental group and the remaining 70% as the non-experimental group. Subsequently, we re-run Eq. (1) to detect the link between the two, as indicated in column (1) of Table 4. One can find that the climate-related information disclosure index also robustly promotes firms' GI, with its corresponding estimate of 0.6388,

Table 3
Baseline regression results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
CIDS	0.7640***	0.9078***	0.9032***	0.9202***	0.7450***	0.7582***	0.7571***
	(0.188)	(0.177)	(0.177)	(0.176)	(0.170)	(0.170)	(0.170)
Cash flow		0.1566*	0.2950***	0.3038***	0.0591	0.0166	0.0165
		(0.087)	(0.091)	(0.091)	(0.088)	(0.091)	(0.091)
Leverage ratio			0.2253***	0.1624***	−0.1077**	−0.0916**	−0.0913**
			(0.043)	(0.043)	(0.044)	(0.044)	(0.044)
Tobin's Q				−0.0329***	−0.0131***	−0.0109***	−0.0109***
				(0.005)	(0.003)	(0.003)	(0.003)
Firm size					0.1238***	0.1307***	0.1308***
					(0.007)	(0.007)	(0.007)
Firm age						−0.0270***	−0.0267***
						(0.008)	(0.008)
Equity concentration							0.0114
							(0.038)
_cons	0.2716***	0.2554***	0.2142***	0.2954***	−0.6526***	−0.6573***	−0.6643***
	(0.014)	(0.013)	(0.015)	(0.019)	(0.053)	(0.053)	(0.058)
Provincial FE	N	Y	Y	Y	Y	Y	Y
Industry FE	N	Y	Y	Y	Y	Y	Y
Year FE	N	Y	Y	Y	Y	Y	Y
Obs.	13664	13664	13664	13664	13664	13664	13664
Adj R-squared	0.0017	0.1388	0.1405	0.1450	0.1776	0.1773	0.1772

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively. CIDS represents the climate-related information disclosure score.

which is significantly positive at the 1% significance level. Moreover, the *inverse Mills ratio* positively correlates with firms' GI, confirming the previous findings. Fortunately, our main regression results remain robust after dealing with the endogeneity induced by the sample self-selection problem (**Appendix A** displays the first-stage regression outcomes of the Heckman two-stage technique.)

Second, note that the underlying characteristics of firms may interest investors. In other words, the variation in firm characteristics may be liable for the heterogeneity of firms' GIs instead of the climate-related information disclosure behavior. Thus, we further certify the credibility of benchmark regression by performing the Propensity Matching Score (PSM) approach. Specifically, we first categorized the test sample into two subgroups according to the industry-year 90th quantile of the climate-related information disclosure indicator (CIDS). Subsequently, we treat firms with the CIDS index more extraordinary than the 90th quantile as the experimental group and other firms as the non-experimental group. Further, the selected firm-level characteristic variables are taken as covariates in the PSM process, and the likelihood of low or high CIDS is forecasted through a logit model. Lastly, the matching sample of the experimental group can be determined from the non-experimental group using the *K*-nearest neighbors matching method. **Appendix A**

Table 4
Robustness checks.

Dep. Var.	(1)	(2)	(3)	(4)	(5)
	GI	GI	GI	GI	GI
Method	Heckman	PSM	IV1	IV2	Two-step GMM
L.GI					0.2956*
					(0.175)
CIDS	0.6388***	1.4794**	0.7805***	0.7370***	0.9185**
	(0.198)	(0.732)	(0.200)	(0.213)	(0.428)
_cons	−0.8860***	−0.6832***	−0.9995***		0.1407
	(0.107)	(0.211)	(0.177)		(0.646)
Mills lambda	0.4249***				
	(0.148)				
Control variables	Y	Y	Y	Y	Y
Provincial FE	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Obs.	13664	996	12206	13664	9956
AR (1)/p-value					−3.66 [0.000]
AR (2)/p-value					1.62 [0.105]
First-stage F value			1.3e+04	1.8e+04	
Hansen J/p-value			[0.000]	[0.000]	13.70 [0.395]
Adj/Pseudo/R-squared	/	0.2447	0.1843	0.0478	

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively. CIDS represents the climate-related information disclosure score. GI denotes the green innovation score. L.GI regulates the lagged term of green innovation score.

Table 5
Heterogeneity results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Industry attribute		Ownership characteristic		Regulation degree		CIDS's four dimensions			
	Clean	Polluting	Non-SOE	SOE	Low	High				
CIDS	1.1026***	−0.1541	0.5126	0.8853***	0.3078	1.0491***				
	(0.207)	(0.218)	(0.330)	(0.193)	(0.238)	(0.229)				
Strategy							0.4125***			
							(0.096)			
Governance								−0.2127**		
								(0.089)		
Risk management									0.0577	
									(0.206)	
Metrics and targets										0.4718***
										(0.164)
Control variables	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Provincial FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
_cons	−0.7745***	−0.1558*	−0.8707***	−0.5789***	−0.7416***	−0.6179***	−0.6537***	−0.6095***	−0.6288***	−0.6544***
	(0.069)	(0.088)	(0.125)	(0.070)	(0.087)	(0.076)	(0.057)	(0.057)	(0.057)	(0.058)
Obs.	10777	2887	3848	9811	5028	8627	13664	13664	13664	13664
Adj R-squared	0.1502	0.3573	0.2076	0.1909	0.1694	0.1816	0.1772	0.1759	0.1756	0.1764

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively. CIDS represents the climate-related information disclosure score.

presents the PSM outcomes. As a result, column (2) of Table 3 shows that the CIDS's estimate remains significant and positive at the 5% significance level, which coincides with the previous estimates.

Third, the 2SLS estimation technique is further applied to verify the reliability of the baseline regression outcomes. Specifically, this study subtracts the average climate-related information disclosure indicator score at the industry level (denoted by specific industry climate-related information disclosure indicator performance) in the relevant year to measure abnormal climate-related information disclosures. The rationale is that dominating leaders (with impactful market power) could potentially inject specific implications in the same industries. For example, thermal-fired generation still accounts for the highest position regarding electricity generation. Yet, individuals who take the lead in adjusting their input matrix by advancing and designing emerging technologies may induce dividends – for example, boosting renewable-fired power generation and minimizing emissions – the resulting influence may thus promulgate to the entire energy sector. In other words, the dedicated instrument captures the deviation between the industry average and the individual. Unsurprisingly, the same procedure can be found in the seminal work of He et al. (2022), who also performed the same path to address endogeneity between retailers' attention and GI. Following He et al. (2022), this study performs 2SLS estimation technique, where the lagged term of abnormal climate-related information disclosure score is introduced as an instrument. Column (3) of Table 4 uncovers that the first-stage F value indicates no weak instrument issue, consolidating the feasibility of the 2SLS regression design. Fundamentally, the coefficient of climate-related information disclosure (CIDS) is still significantly positive, consistent with the baseline outcomes.

Regarding the 2SLS estimation, this study constructs a new instrument to ascertain the climate-related information disclosure-GI nexus further. Building the instrument at the micro level is challenging; instead, the instrument in our exercise is established by computing the product between newspaper type within a county and a temporal dummy (Tao et al., 2022). The purpose of multiplying temporal dummies lies in solving time-invariant concerns. Theoretically, this study holds the following rationales to justify the relevance and exogeneity. The closure of newspaper types in a particular region can have implications for the construction of firms' reputations within that region (Jiménez et al., 2022). For example, newspapers often serve as important channels for reporting on corporate activities, including climate-related information disclosure initiatives, performance, and controversies. When newspapers close or reduce their coverage, there is a decrease in media outlets available to report on firms' climate-related information disclosure-related activities and developments. This reduction in media coverage can limit the visibility and exposure of firms' climate-related information disclosure efforts, making it more challenging for stakeholders to access relevant information about their environmental, social, and governance practices. Also, climate-related information disclosure plays a crucial role in shaping investor perception, decision-making, and investment strategies. Investors rely on media coverage and news reports to gather information about firms' climate-related information disclosure performance and assess their sustainability credentials. The closure of newspapers can lead to a lack of timely and comprehensive climate-related information disclosure reporting, making it difficult for investors to evaluate firms' sustainability practices and integrate climate-related information disclosure factors into their investment decisions. Therefore, the newspaper types have a direct connection with corporate climate-related information disclosure. Notably, increasing newspaper types does not contribute appreciably to a firm's GI performance. Thus, the exogeneity is satisfied. After addressing the potential connections, we perform 2SLS estimation, as depicted in column (4) of Table 4. Essentially, there is also a positive connection between climate-related information disclosure and firm GI performance, with the corresponding estimate of 0.7370, passing the 1% significance level. Regarding the estimate's effectiveness, the first-stage F value is greater than 10, consolidating the creditability of benchmark validation.

Lastly, considering the dynamic effect of corporate GI progress, this study further executes the dynamic panel data model, e.g., two-step GMM. Column (5) of Table 4 gives the relevant estimates. First, the lagged GI values are significant and positive at the 10% significance level, suggesting that previous GI accumulation generates substantial contributions to current GI progress. Second, we consider the effectiveness of the two-step GMM technique. For example, there is first-order autocorrelation without higher-order ones, as evidenced by the typical fact that AR (1)'s coefficient is salient, yet AR (2) is insignificant. At the same time, the insignificance of Hansen J statistic further certifies the efficacy of the constructed instruments. At the same time, The F value of the two-step GMM estimate in column (5) is 172.90 (p-value = 0.000), validating the effectiveness of the model evaluation. Third, our central indicator, CIDS, remains positive and significant, certifying the reliability of previous verification. In other words, climate-related information disclosure still exerts salient promoting effects on corporate GI after considering potential dynamic effects. Hence, **H1** is supported.

5. Further analyses

5.1. Heterogeneity analysis

Firms' innovation intentions vary across heterogeneous attributes; thus, their climate-related information disclosure behaviour may also differ. Specifically, pollution-intensive enterprises featured by high energy consumption and high-polluting emissions may bear more abatement costs to mitigate their emissions and re-articulate the energy mix. As a result, this motivates us to validate the potential heterogeneous effects. Columns (1) & (2) of Table 5 present the relevant estimates. We can see that those firms in cleaner industries exhibit higher GI performance, which is in striking contrast to those reluctant to disclose climate-related information. Therefore, **H2a** is supported. According to the behavioural consistency theory, firms' behavioural patterns can be used to predict their performance in different areas (Funder and Colvin, 1991). Investors or stakeholders in more polluting industries will scrutinize firms in the same industry even if they have strong social and governance performance, increasing the risk premium and reducing their investment confidence (Li et al., 2023). Cleaner industries, on the other hand, are more likely to gain investors' trust, enhance green investments, and further strengthen firms' GI capabilities.

Second, GI behaviour may also vary according to firms' ownership structures, especially in the Chinese market where SOEs are prevalent. It is important to validate the potential heterogeneous effects based on firm attributes: SOEs vs. non-SOEs. In particular, the relevant estimates in columns (3) & (4) reveal that the climate-related information disclosure score promotes GI more significantly regarding the magnitude and significance of the estimates for SOEs than non-SOEs. Hence, **H2b** is also supported. This is because SOEs are in a mature development stage, while most non-SOEs are in an upward stage. Compared to mature firms, firms in the growth stage have incomplete information disclosure and higher information costs and face the dual dilemma of higher capital needs than financing constraints, thus resulting in limited development of GI (Tan & Zhu, 2022).

Third, we consider the stringency of environmental regulation. We follow Wu et al. (2020) to compute China's interprovincial environmental regulation index; subsequently, the test sample is categorized into two sub-groups by comparing the sample average. In columns (5) & (6) of Table 5, the estimates indicate that the effect of climate-related information disclosure on corporate GI tends to be tremendously strengthened in regions with higher environmental regulations. The results show that our **H3c** can be accepted. This aligns with Porter & Linde (1995), who also pinpointed that an enterprise's innovation is highly contingent upon environmental regulations. Moreover, Tan and Zhu (2022) argue that climate information disclosure can alleviate the information asymmetry between environmental regulators and firms, enhance firms' green goodwill and market value, and provide sufficient financial support for GI, even with strict environmental regulation. Moreover, a strict regulatory environment will stimulate firms to form more effective institutional norms and regulations, strengthens social legitimacy, makes obtaining external resources needed for green growth more accessible, and stimulates GI capacity (Alrazi et al., 2015).

Lastly, we examine the effects of four dimensions of climate-related information disclosure on corporate GI separately, as listed in columns (7)–(10) of Table 5. Specifically, sub-dimensions, like strategy, risk management, and metrics and targets, positively correlate with corporate GI, with the corresponding effect of risk management being insignificant. In contrast, governance significantly depresses corporate GI. The above findings yield the following justifications. This may be explained by the fact that enterprises have formulated proactive plans at the strategic level to promote the adoption or development of more environmentally friendly technologies and that they have set clear green technology innovation metrics to help them track and manage their progress, which is an effective way of encouraging them to engage in green technology innovation actively. The negative trend in the "governance" sub-indicator may be due to a lack of transparency in the corporate governance structure or a lack of willingness or support for GI from top decision-makers, which may have hindered the development of GI in the enterprise.

5.2. Mechanism tests

Following the research hypotheses, we validate the nexus between climate-related information disclosure and corporate GI through three aspects: greenwashing behaviour (GW), digital finance (DF), and financial constraints (FC).

First, referring to Zhang (2022), GW can be conceptualized as a business pursuing a public and social image by any means necessary for the sake of consumers and financial lenders. In other words, market participants may not function well, but they must disclose environmentally relevant information to gain a reputation under well-established environmental regulations; otherwise, they may face penalties or bankruptcy. Therefore, the standard calculation formula for the firm-level GW index is as follows:

$$GW_{it} \stackrel{\text{def}}{=} [(ESG_{it} - \overline{ESG}_{it})/\sigma_{ESG}] - \left[\left(ESG_{ranking_{it}} - \overline{ESG}_{ranking_{it}}\right) \Big/ \sigma_{ESG_{ranking}}\right] \tag{4}$$

Table 6
Mechanism analysis results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CIDS	0.9388***	0.8383***	0.7357***	0.6267***	0.3169	0.1684	9.0626***	12.6879***
	(0.216)	(0.207)	(0.190)	(0.183)	(0.254)	(0.249)	(3.483)	(4.315)
CIDS#GW dummy	−0.3578**	−0.3837**						
	(0.179)	(0.173)						
CIDS#GW			−0.1041	−0.1291*				
			(0.074)	(0.071)				
CIDS#DF					0.8058***	0.8488***		
					(0.266)	(0.260)		
CIDS#FC							−2.6340**	−3.8030***
							(1.093)	(1.359)
Control variables	N	Y	N	Y	N	Y	N	Y
Provincial FE	Y	Y	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
_cons	0.2724***	−0.5834***	0.2745***	−0.5786***	0.2690***	−0.5925***	0.2680***	−0.4759***
	(0.014)	(0.058)	(0.014)	(0.060)	(0.014)	(0.059)	(0.014)	(0.057)
Obs.	13664	13664	13185	13185	13616	13616	13054	13054
Adj R-squared	0.0028	0.0507	0.0024	0.0496	0.0034	0.0512	0.0024	0.0416

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively. CIDS represents the climate-related information disclosure score. GW means the greenwashing score. DF represents the digital finance score. FC is the financial constraint score.

where ESG_{it} and $ESG_{ranking_{it}}$ specify the ESG score and the corresponding score ranking in the i-th firm at year t, respectively; σ_{ESG} represents the standard deviation of the corresponding index. In particular, the ESG score disclosure comes from the Bloomberg ESG database, and the ESG ranking data is extracted from the WIND database.

Columns (1)–(4) of Table 6 display the joint effect of climate-related information disclosure and GW behaviour on firms' GI. First, for "greenwashed" firms, we combine the GW dummy variable with climate-related information disclosure to test their joint impact on corporate innovation. We can see that the combined effect of the GW dummy variable and climate-related information disclosure is significant and negative before and after controlling for firm-level characteristic variables. The same findings can be observed in columns (3) & (4), where we replace the GW dummy with the actual GW value. Considering the high cost of environmental practices, many companies improve their green-related disclosure through GW, which does not imply real corporate action on climate change, decoupling it from their commitments and failing to achieve GI's fundamental purpose (Hu et al., 2023). In other words, firms' GW behaviour reduces firms' practice to combat climate change and, therefore, performs poorly in green outcomes, acting as a negative influence (Mateo-Márquez et al., 2022). In addition, the possibility of corporate GW is driven by the fact that under climate constraints, firms are forced to disclose their climate strategies to maintain their legitimacy (Linares-Rodríguez et al., 2023). Because of this, Wedari et al. (2021) find a negative correlation between climate-related information disclosure and environmental performance due to GW. Furthermore, the effects of the three mechanisms under industry attribute, ownership characteristic, and environmental regulation degree heterogeneity are shown in **Appendices B1-B3**, respectively. In terms of GW behaviour, it effectively inhibits the positive effects of climate-related information disclosure and GI of polluting enterprises and firms with low environmental regulation (see column (4) in **Appendix B1** and column (3) in **Appendix B3**). Conclusively, polluting enterprises and firms with low environmental regulation programs are inherently green dilemmas. GW behaviours will only lead to more disillusionment and withdrawal of investment by stakeholders. Moreover, firms may satisfy minimum regulatory requirements through superficial green behaviours and reduce investment in R&D and environmental technologies, thus inhibiting authentic GI.

Second, given the critical role of digital finance in eliminating financial constraints and promoting sustained green development, we certify the joint effect between DF and climate-related information disclosure. Specifically, the Digital Finance Index is jointly structured by Ant Gold Group Research Institute and Peking University's Institute of Digital Finance. This index comprises three fundamentals: coverage breadth, usage depth, and degree of digitalization. Notably, the sub-indicator is extracted from Ant Financial Services Group's trading accounts, a broad dataset that makes our DF data more reliable. Therefore, we follow Li et al. (2020) and utilize China's digital financial inclusion index to proxy digital finance. Evidence from columns (5) & (6) of Table 6 shows that the relevant joint effect contributes robustly to corporate GI with and without covariates. We suspect the following potential reasons. First, DF can reduce the information gap, lowering the information asymmetry between firms and external green investors, reducing the risk of investor uncertainty, and making green and climate change-related investments more accessible (Lu et al., 2022). Moreover, DF has a cost reduction effect, which saves financing and information costs and attracts more capital into corporate environmental information disclosure and green technology investment (Ren et al., 2023). Finally, DF can improve the quality of information disclosure through the ability of modern science and technology techniques to provide companies with more appealing climate information to investors, strengthen the confidence of investors and stakeholders, and achieve an increase in green technology investment (Yee et al., 2018). From the results of the heterogeneous DF mechanism, it can promote the positive effect of climate-related information disclosure and GI in polluting, SOEs and non-SOEs (see Column (6) in **Appendix B1**, Columns (5)–(6) in **Appendix B2**). This suggests that a universal system of DF within the above three industries positively impacts corporate GI, which also provides an effective practical route to carry out GI in the above three sectors.

Third, we further validate the potential channels between climate-related information disclosure and corporate GI from a financial constraint perspective. In our case, we measure the corporate FC index by referring to Rahman (2023), with the formula below:

$$FC_{it} = -1.002 * \frac{CF_{it}}{Assets_{i,t-1}} - 39.368 * \frac{CD_{it}}{Assets_{i,t-1}} - 1.315 * \frac{CB_{it}}{Assets_{i,t-1}} + 3.139 * Leverage_{it} + 0.283 * MV_{it} \quad (5)$$

where CF_{it} denotes the cash flow; CD_{it} represents the cash dividends; CB_{it} regulates the cash balance; $Leverage_{it}$ is the leverage; MV_{it} means the equity market value; $Assets_{i,t-1}$ is the lagged period of assets.

The relevant estimates presented in columns (7) & (8) indicate that corporate FC could turn CIDS's positive effects into adverse effects, depressing the corporate GI process. Due to the information asymmetry theory, it is known that firms can disclose high-quality environmental information to obtain resources from stakeholders and strengthen their GI capability. Moreover, FC will weaken the chain (Tan & Zhu, 2022). While enterprises facing FC are unable to freely adjust their capital structure, which restricts their development, from the internal consideration of enterprises, they usually save money and reduce expenses by reducing R&D investment; from the external consideration of enterprises, it is more difficult for them to obtain valuable asset and their credit is damaged (Revell et al., 2010; Zhang & Lucey, 2022). From the heterogeneous FC mechanism perspective, FC effectively inhibits the positive association between climate disclosure and firms' GI for clean firms, polluting firms, non-SOEs, and enterprises with high environmental regulations (see Columns (7)–(8) in **Appendix B1**, Column (7) in **Appendix B2**, and Column (8) in **Appendix B3**). This suggests that FC is an insurmountable stumbling block for most enterprises on their way to achieving GI. Investors are more inclined to invest green funds in more regulated and secure SOEs and less constrained low-environmental regulation enterprises, which results in FC becoming a problem for non-SOEs and high-environmental regulation enterprises. Thus, the government should strengthen financial incentives and support for the above industries to guide enterprises in investing and realizing GI.

6. Conclusions

In the background of China's "carbon neutral" target, climate and environmental disclosure constrain corporate production behaviour and promote corporate green transformation, which may enhance corporate GI capacity. Based on this, this paper evaluates the impact of corporate climate disclosure on GI by utilizing a panel of Chinese A-share listed companies from 2014 to 2020. Further, this paper also assesses industry heterogeneity, property rights heterogeneity, environmental regulation heterogeneity, and sub-dimension heterogeneity. Finally, we also explore the mechanism between climate-related information disclosure and corporate GI from three perspectives: greenwashing behaviour, digital finance, and financial constraints. We mainly obtained the following research conclusions: First, climate-related information disclosures powerfully contribute to firms' GI, with significant heterogeneous effects on its sub-indexes. Second, the heterogeneity results show that cleaner firms, SOEs, and strict environmental regulations will effectively strengthen the positive impact between climate-related information disclosure and firms' GI. Finally, firms' "greenwashing" behaviour and financing constraints reverse the facilitating effect of climate disclosure on firms' GI, while digital financial inclusion reinforces this effect. Based on these findings, we have the following policy implications.

First, this study's findings favour both enterprises and policies. Enterprises can identify and disclose climate- or environment-related information promptly to address the concerns of critical stakeholders, attract their green investment, and realize GI and upgrading for the government; they should improve the disclosure rules of climate-related information, formulate more detailed and scientific disclosure specifications, and guide enterprises to realize GI.

Second, given the results of the heterogeneity analysis, the government and enterprises should strengthen their attention to polluting and non-SOEs, enhance government financing, and provide technical and financial support to investors. Thus, enterprises can complete the green transition more quickly. This effectively avoids the vicious circle of enterprises not obtaining green investment and being in a problematic green transformation. At the same time, the government should establish a perfect environmental regulation system, strengthen environmental supervision, improve the details of climate-related information disclosure, and reduce information asymmetry.

Finally, the government needs to focus on two obstacles that may exist in disclosing corporate climate-related information. i) GW behaviour. It can lead to enterprises cheating on green investment without innovation; the government should strengthen the supervision of information disclosure to prevent false behaviour. ii) FC. The government can formulate a particular incentive program to provide financial incentives to enterprises with better disclosure of climate-related information, which can help enterprises realize green transformation and revive investors' confidence. Correspondingly, enterprises can strengthen the ability of digital financial inclusion, expand the scope of information technology development, help enterprises obtain more green financing, establish a close partnership with investors, and realize GI enhancement.

Although our study provides new insights into the literature and practices, there remain several limitations. One limitation is that the results of this study are based on a sample of Chinese firms and may not be generalizable to firms in other countries, especially those in developed markets that tend to exhibit unique forms of environmental responsibility (Doh et al., 2015). We encourage future studies to conduct follow-up studies to examine the relationship between climate-related information disclosure and green innovation of firms from other countries or to compare the GI behaviour of firms from different countries (Wu et al., 2014). Furthermore, although we conducted additional tests to validate the relationship considering the heterogeneous firm-level attributes, we did not examine how variations from the managerial aspect may revise the relationship due to data limitations. Yet, prior research shows that leaders' green orientation, CEO-TMT power disparity, and different management styles of firms can affect firms' environmental practices (e.g., Kwon et al., 2023). Therefore, we suggest researchers to examine other important firm-level attributes that can shed light on this topic and further reveal the underlying mechanisms that can revise the nexus between climate-related disclosure and green innovation of firms.

List of variables.

Variable	Definition	Source
CIDS	See Section 3.2	WIND
Cash flow	The firm's net profit * Total assets	WIND
Leverage ratio	Corporate leverage/Total assets	WIND
Tobin's Q	Corporate market capitalization/Asset replacement cost	WIND
Firm size	The logarithm of the total number of employees	WIND
Firm age	The logarithm of the firm's duration in the market	WIND
Equity concentration	The sum of the top ten shareholders' ownership ratio	WIND
GW	Greenwashing	WIND
DF	Digital finance	See note
FC	Financial constraints	WIND

Note: The data related to digital finance is sourced from Ant Gold Group Research Institute and Peking University's Institute of Digital Finance.

Data availability

The authors do not have permission to share data.

Appendix A. The first-stage results of the Heckman estimation

Dep. Var.	(1)	(2)
	CIDS	CIDS
Method	Heckman	PSM
Cash flow	0.1363	0.8890
	(0.189)	(0.573)
Leverage ratio	−0.1271	−0.2894
	(0.085)	(0.245)
Tobin's Q	0.0136*	0.0401**
	(0.007)	(0.020)
Firm size	0.0438***	0.0760**
	(0.007)	(0.031)
Firm age	0.0211	0.0241
	(0.015)	(0.041)
Equity concentration	0.1228*	0.3777*
	(0.064)	(0.205)
Provincial FE	Y	Y
Industry FE	Y	Y
Year FE	Y	Y
Obs.	13664	13664

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively.

Appendix B1. Heterogeneity results based on mechanism analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Industry attribute		Industry attribute		Industry attribute		Industry attribute	
	Clean	Polluting	Clean	Polluting	Clean	Polluting	Clean	Polluting
CIDS	0.5284**	1.0976***	0.6165***	0.8277***	0.4308	0.2470	21.2654***	15.7333**
	(0.234)	(0.296)	(0.215)	(0.271)	(0.291)	(0.443)	(5.823)	(6.875)
CIDS#GW dummy	0.0641	−0.3558						
	(0.213)	(0.246)						
CIDS#GW			−0.0175	−0.1758*				
			(0.083)	(0.104)				
CIDS#DF					0.0058	1.0567**		
					(0.334)	(0.422)		
CIDS#FC							−6.5127***	−4.7024**
							(1.822)	(2.160)
Control variables	Y	Y	Y	Y	Y	Y	Y	Y
Provincial FE	Y	Y	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
_cons	−0.6488***	−0.7046***	−0.6434***	−0.7031***	−0.5472***	−0.6064***	−0.6088***	−0.5805***
	(0.080)	(0.086)	(0.082)	(0.089)	(0.080)	(0.088)	(0.080)	(0.085)
Obs.	4347	7879	4162	7569	4313	7875	4232	7585
Adj R-squared	0.1736	0.1789	0.1734	0.0757	0.0522	0.0540	0.1545	0.1696

Notes: Values outlined in (.) represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively.

Appendix B2. Heterogeneity results based on mechanism analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ownership characteristic		Ownership characteristic		Ownership characteristic		Ownership characteristic	
	Non-SOE	SOE	Non-SOE	SOE	Non-SOE	SOE	Non-SOE	SOE
CIDS	0.6483	0.9774***	0.5956*	0.8423***	1.8517***	0.0584	35.4667***	5.8030
	(0.406)	(0.223)	(0.361)	(0.209)	(0.633)	(0.429)	(7.483)	(6.247)
CIDS#GW dummy	−0.2600	−0.1106						
	(0.328)	(0.199)						

(*continued on next page*)

(*continued*)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ownership characteristic		Ownership characteristic		Ownership characteristic		Ownership characteristic	
	Non-SOE	SOE	Non-SOE	SOE	Non-SOE	SOE	Non-SOE	SOE
CIDS#GW			−0.0623	−0.0961				
			(0.127)	(0.086)				
CIDS#DF					2.6382***	1.1907*		
					(0.893)	(0.653)		
CIDS#FC							−10.9232***	−1.5947
							(2.354)	(1.957)
Control variables	Y	Y	Y	Y	Y	Y	Y	Y
Provincial FE	Y	Y	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
_cons	−0.9347***	−0.6051***	−0.9586***	−0.5940***	−0.9422***	−0.4568***	−0.6130***	−0.4648***
	(0.131)	(0.078)	(0.133)	(0.080)	(0.131)	(0.079)	(0.120)	(0.079)
Obs.	3479	8750	3346	8389	3468	8715	3251	8570
Adj R-squared	0.2166	0.1939	0.2158	0.1936	0.2189	0.0524	0.2017	0.1838

Notes: Values outlined in () represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively.

Appendix B3. Heterogeneity results based on mechanism analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Regulation degree		Regulation degree		Regulation degree		Regulation degree	
	Low	High	Low	High	Low	High	Low	High
CIDS	1.1267***	0.4903*	1.0097***	0.3482	0.9133**	0.1789	5.4920	39.9388***
	(0.272)	(0.288)	(0.269)	(0.261)	(0.432)	(0.339)	(6.243)	(6.804)
CIDS#GW dummy	−0.1430	−0.3092						
	(0.226)	(0.261)						
CIDS#GW			−0.2034**	−0.1145				
			(0.085)	(0.109)				
CIDS#DF					0.1461	0.0803		
					(0.438)	(0.469)		
CIDS#FC							−1.4196	−12.4882***
							(1.961)	(2.130)
Control variables	Y	Y	Y	Y	Y	Y	Y	Y
Provincial FE	Y	Y	Y	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
_cons	−0.6333***	−0.7474***	−0.5180***	−0.7659***	−0.6416***	−0.7498***	−0.5048***	−0.6893***
	(0.082)	(0.098)	(0.085)	(0.101)	(0.082)	(0.098)	(0.078)	(0.099)
Obs.	7786	4438	7499	4236	7765	4412	7537	4281
Adj R-squared	0.1853	0.1745	0.0508	0.1752	0.1822	0.1610	0.1754	0.1685

Notes: Values outlined in () represent the robust-heteroskedasticity standard errors; *, **, and *** regulate the significance level tests of 10%, 5%, and 1%, respectively.

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