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When does ESG drive corporate green transformation? A dual-contingency perspective of climate risk and financial constraints

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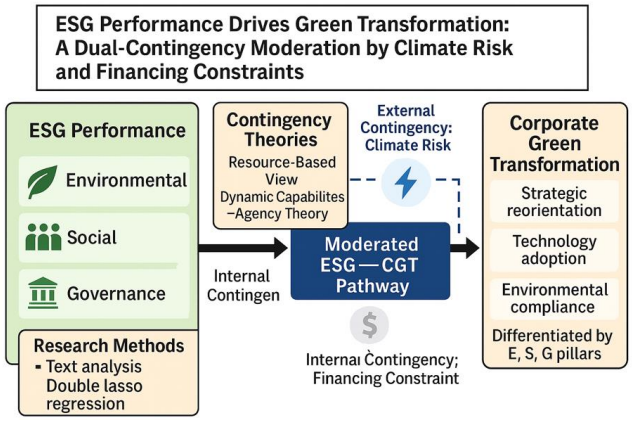
Graphical abstract



Abstract

In the face of accelerating climate change and rising stakeholder expectations, Environmental, Social, and Governance (ESG) strategies have emerged as vital instruments in guiding corporate green transformation (CGT). Whether these programs are effective in achieving sustainability, however, still depend on firms' unique contexts. Therefore, this study develops a dual-contingency model that integrates Contingency Theory with the Resource-Based View and Dynamic Capabilities Theory to determine the combined effects of external climate risk and internal financing limitations on the ESG–sustainability relationship. We apply text-mining and double-selection LASS estimation to analyze a panel dataset of Chinese listed firms from 2009 to 2023. The results indicate that of the three ESG dimensions, the environmental and governance pillars significantly enhance firms' green transformation. This effect, nonetheless, is weakened by climate risk and financing limitations, confirming ESG's context-specific impact. Our findings add to the theoretical knowledge of ESG's dynamic mechanism and provide firms actionable recommendations in managing both environmental and resource volatilities. The results show that environmental and governance pillars play a key role in driving green transformation, yet their effectiveness is highly context-dependent. Both climate risk and financial constraints attenuate ESG impacts, with regional SHAP analysis revealing that governance practices are particularly valuable under climate uncertainty, while financial frictions exacerbate ESG implementation gaps. This study advances ESG research by integrating econometrics and machine learning to uncover its conditional effectiveness, offering practical insights for firms navigating sustainability under climate and financial stress.

Keywords: ESG; Corporate Green Transformation; Climate Risk; Financing Constraints; Double-Selection LASSO

1. Introduction

Over recent decades, growing ecological concerns and social scrutiny have driven corporate sustainability to the forefront of business management. Stakeholders, particularly environment-conscious investors and consumers, are becoming increasingly well-informed, compelling firms to proactively and effectively address escalating sustainability pressures (Xue *et al.* 2024). Against this backdrop, this research focuses on the rapid adoption of Environmental, Social and Governance (ESG) frameworks by organizations worldwide. As practices that signal authentic commitment to sustainability, ESG initiatives span a firm's efforts to alleviate its environmental footprint, advance social equity, and implement transparent, accountable governance systems (Aleksy *et al.* 2023; Wang *et al.* 2023). For firms to strategically recalibrate towards ESG, they must execute corporate green transformation (hereafter CGT): the organization-wide integration of sustainable business models that lower pollution, boost resource efficiency, and strive towards a low-carbon future (Porter & van der Linde 1995; Ren *et al.* 2024).

Although ESG's transformative potential is widely acknowledged, the mechanisms by which ESG practices translate into measurable environmental gains remain

complex and context-specific. It has been established that firms with stronger environmental management typically adopt green innovations more readily (Eccles *et al.* 2014; Xie 2024). However, the crucial role of climate risk in ESG's impact is still ambiguous, necessitating further research (Chen *et al.* 2022). The complex dynamics of climate risk extend beyond immediate physical threats such as extreme weather or supply-chain disruptions; climate risk also exerts transitional pressures, arising from emerging regulations, market changes, and growing consumer demand for sustainable products (Vannoni & Ciotti 2020; Sun *et al.* 2024). These intertwined climate challenges create strategic dilemmas that alter the effectiveness of ESG initiatives in green transformation (Aleksy *et al.* 2023).

China provides a compelling context for this phenomenon. The nation's ambitious carbon-neutral targets, rapidly-evolving regulatory landscape, and strong state involvement in corporate governance have created ESG dynamics that differ markedly from those in Western economies (Wang *et al.* 2023). In light of these distinctive features, this study aimed to fill knowledge gaps on whether climate risk moderates the impact of ESG on green transformation among Chinese firms (Xue *et al.* 2024). In other words, do growing climate threats catalyze firms to intensify their ESG-based green transformation, or do they instead caution firms to use ESG merely as a protective strategy?

Most studies have assumed a linear direct relationship between firms' ESG adoption and environmental performance. Contrary to this perspective, we draw on the Contingency Theory, the Resource-Based View (RBV), and the Dynamic Capabilities Theory (DCT) to argue that the ESG–CGT nexus is conditional. Therefore, we innovatively propose a dual-path moderation framework that conceptualizes climate risk (external contingency) and financing constraints (internal contingency) as contextual factors moderating the extent to which ESG initiatives elicit CGT (Sun *et al.* 2024).

Our research objectives are as follows: (i) to identify the direct impacts of individual ESG pillars (environmental, social, and governance) on CGT (Eccles *et al.* 2014; Xie 2024) and (ii) to determine the moderating roles of climate risk and financing constraints in the ESG–CGT nexus. Integrating these perspectives elucidates the nuanced interaction between ESG and climate change, offering the corporate sustainability discourse a deeper understanding of the conditions under which ESG truly matters for sustainability within China's evolving institutional setting (Wang *et al.* 2023; Aleksy *et al.* 2023). The findings provide critical insights into firms' adaptive strategies to resist external and internal pressures (Chen *et al.* 2022; Vannoni & Ciotti 2020), thus aiding managers and policymakers striving for long-term economic resilience and sustainability (Ren *et al.* 2024; Aleksy *et al.* 2023).The remainder of this paper is organised as follows. Section 2 provides a comprehensive review of relevant literature and theoretical frameworks, including the Resource-Based View (RBV), Dynamic Capabilities Theory (DCT) and the theory of environmental externalities. It synthesises prior findings on the role of ESG performance, climate risk exposure, and organizational resilience, identifying critical gaps in the current understanding and outlining the conceptual basis for this study. Section 3 delineates the data, methodology, and research design employed in this study. It explicates the data sources, which encompass firm-year observations derived from Bloomberg ESG scores, financial statements, and corporate climate risk disclosures. This section also elucidates the econometric models utilized, notably the Generalized Method of Moments (GMM) approach, which addresses potential endogeneity issues and ensures the robustness of the estimated relationships. Furthermore, it details the process of constructing the climate risk index through text-mining techniques, including Term Frequency-Inverse Document Frequency (TF-IDF), to capture the extent of climate-related exposure for each firm. Section 4 presents the empirical results and analysis, emphasizing the differential impacts of ESG subdimensions (Environmental, Social, Governance) on corporate green transformation (CGT). It highlights the varying contributions of each dimension, reflecting the unique pathways through which firms achieve sustainability. This section also explores the moderating effects of climate risk and financing constraints, capturing the critical thresholds at which these factors influence the effectiveness of ESG initiatives. To ensure the robustness and reliability of the results, the analysis includes a series of validation checks, including counterfactual simulations and sensitivity analyses, confirming the stability of the observed relationships across different model specifications. Section 5 discusses the findings in the context of existing literature, outlining their theoretical and practical implications. This section explores the broader impact of ESG strategies on long-term economic resilience, offering insights for managers and policymakers aiming to enhance sustainability. Section 6 concludes the study by emphasizing its significant contributions to the understanding of ESG-climate resilience. It acknowledges the limitations inherent in the analysis, such as data coverage and geographic scope, and offers recommendations for future research. These include extending the analysis to encompass emerging markets and integrating blockchain-enabled ESG reporting.

2. Literature Review and Hypothesis Development

2.1. Theoretical Foundation

Our framework is grounded in three well-established theories: the Contingency Theory, the RBV, and the DCT. First, Contingency Theory holds that organizational outcomes depend not only on internal attributes, but also on the fit between these attributes and external conditions (Donaldson 2001; Lawrence & Lorsch 1967). In this regard, climate risk constitutes a progressive and volatile external force that may impede or boost a firm's sustainability efforts based on its internal adaptive capacity (Sun *et al.* 2024; Chen *et al.* 2022).

The RBV, meanwhile, highlights a firm's resources as sources of competitive advantage, theoretically underpinning how ESG can promote CGT (Barney 1991; Wernerfelt 1984). The RBV argues that long-term competitive advantage stems from firm-specific resources that are valuable, rare and hard to imitate (Barney 1991). Correspondingly, ESG capabilities, especially those related to the environment, are useful resources that improve firms' innovativeness and adaptability in the face of external market shifts (Jin & Lei 2023; Lei 2024). Firms that channel capital into energy-saving technology or green R&D can build assets that competitors struggle to imitate, helping them achieve CGT, long-term profitability, and market leadership (Wang *et al.* 2023; Ren *et al.* 2024; Lei & Xu 2024b).

Complementing the RBV, the DCT stresses the imperative for firms to leverage their dynamic capabilities to respond to environmental pressures like new eco-laws and market demands (Teece 2007). Robust capabilities allow firms to continuously innovate, adapt, and recalibrate their resources, granting these firms the agility to easily embed ESG into operations and achieve green transformation (Wu *et al.* 2024; Yuan *et al.* 2024). Such agility is crucial for CGT. In addition, environmental externality theory from environmental economics provides a foundational rationale for ESG-driven green transformation. Firms' environmental activities generate external social costs, such as pollution, which are often unpriced by markets. ESG performance—especially the environmental dimension—can be viewed as an internalization mechanism to reduce negative externalities and align private costs with social costs (Wang *et al.* 2023; Li *et al.* 2024; Lei & Xu 2024a). This corrective process supports the economic legitimacy of ESG-driven transformation as a cost-effective response to regulatory pressures, reputational risks, and long-term sustainability expectations (Huang *et al.* 2024; Whited & Wu 2006; Hadlock & Pierce 2010).

2.2. ESG and CGT

In sustainable business research, the link between a firm's ESG implementation and green transformation has become a key focus area. CGT in a firm entails the process of adopting eco-friendly strategies to alleviate carbon footprint, increase energy efficiency, and support a low-carbon economy. Empirical findings have validated that robust ESG initiatives can significantly promote green transformation by reshaping corporate behavior, innovation, and resource distribution (Wang *et al.* 2023; Xie 2024). The three pillars of ESG are explained below.

Environmental (E): The environmental pillar of ESG concentrates on how firms handle ecological issues, from curbing their carbon emissions to reducing waste and practicing 'greener' production. Environmentally friendly firms that invest in cleaner technologies and resource-efficient processes demonstrate better green transformation. By actively reducing environmental externalities, these firms not only comply with regulations but also improve reputational capital and operational efficiency, forming the economic basis for voluntary sustainability actions (Ren *et al.* 2024; Yuan *et al.* 2024).

Social (S). ESG's social pillar refers to a firm's relationships with its workers, customers, and communities, which can affect CGT. Firms that prioritize social responsibility are more likely to align their people practices (e.g., fair labor, diversity, and community support) with market/stakeholder expectations of sustainability. In doing so, they win stakeholder trust and establish a good reputation, generating a positive feedback loop that enables them to commit to green transformation (Xi & Wang 2024; Wu *et al.* 2024).

Governance (G). The governance pillar of ESG reflects the systems and procedures that guide corporate decisions. Robust governance structures embed sustainability goals in strategy, integrate accountability mechanisms, ensure compliance with environmental regulations, and improve risk management (Dai & Zhu 2023). Altogether, these governance aspects improve firms' capability to invest in green projects and achieve CGT (Lian *et al.* 2023; Chen *et al.* 2023).

Evidently, the literature positions ESG dimensions as vital contributors to CGT based on the RBV and DCT. Higher ESG performance, particularly in the environmental and governance pillars, helps firms attain unique resources, system efficiency, green innovation, and adaptive strengths. Meanwhile, environmental economics highlights ESG's role in internalizing external costs and mitigating sustainability-related market failures. These dynamic capabilities equip firms with better adaptability to external changes and green transformation success, ensuring a sustainable competitive advantage. Therefore, it is hypothesized that:

Hypothesis 1: ESG performance positively influences CGT.

2.3. Climate Risk as an External Moderator

Climate risk exerts a complex influence on the ESG–CGT nexus. It refers to both physical threats (e.g., resource depletion, extreme weather) and transition pressures (e.g., new regulations, market demand for low-carbon goals) (Chen *et al.* 2024; Zhang *et al.* 2024a). These forces shape how firms deploy resources, meet stakeholder expectations and adopt sustainability strategies, thereby determining the strength of ESG's effect on CGT.

As per the RBV, climate risk can amplify or erode the value of ESG-related assets. Firms that are highly vulnerable to climate threats typically encounter stricter regulatory oversight and operational disruption. In such situations, ESG can be a strategic risk-mitigating resource that facilitates compliance, efficiency, and stakeholder confidence (Zhang *et al.* 2024b). For example, investments in clean technology and sustainable governance mechanisms improve a firm's capacity to navigate evolving climate laws and market demands, amplifying ESG's positive contribution to green transformation via effective resource usage (Li 2024a). At the same time, severe climate pressures can hamper this relationship when companies lack the capacity to uphold ESG while

facing climate risks (Qing *et al.* 2024). Firms under such resource constraints, especially in resource-intensive sectors or high-risk regions, thus struggle to transform ESG practices into tangible sustainability results (Chen *et al.* 2024).

The DCT supports this dual effect. Businesses with robust dynamic capabilities are better equipped to modify their ESG approach when climate threats emerge. They may, for instance, reinforce their environmental strategies and governance structures to mitigate climate risks, thereby heightening the effect of ESG on CGT (Zhang & Chen 2023). On the other hand, firms with fewer dynamic capabilities are not agile enough to adapt to sudden climate issues, yielding inconsistent green transformation results (Yan *et al.* 2024).

Overall, climate risk's moderating role in the ESG-CGT link is likely context-dependent; it may either catalyze firms to strengthen ESG performance or, conversely, threaten the effectiveness of existing ESG measures. As such, we hypothesize that:

Hypothesis 2: Climate risk moderates the positive influence of ESG performance on CGT.

2.4. Financing Constraints as an Internal Moderator

Agency Theory (Jensen & Meckling 1976) underscores that investor trust, transparency, and financial stability largely determine a firm's capital resource acquisition. While ESG credentials are often touted as strategic assets, converting them into actual environmental gains relies on a firm's ability to plan for the long-term while withstanding short-term financial pressures (Xue *et al.* 2024). Accordingly, access to financing is a crucial yet nuanced determinant of firms' green transformation.

Firms that champion ESG can be limited by financing, leaving them unable to fulfill their sustainability goals. For example, a company adopting ESG for green transformation would be curtailed without capital to invest in the required green technologies, sustainable operation systems, and eco-friendly infrastructure. Financing constraints are thus not just minor nuisances but significant roadblocks to the ESG-CGT effect. Merely committing to ESG is not sufficient to overcome pronounced funding shortages, weakening the positive ability of ESG to transition a firm towards a green future. On the other hand, firms with abundant financial assets or funding access possess an agile advantage, as they are able to proactively invest in ESG practices (e.g., latest green technologies, renewable energy systems, product innovations) to attain visible, measurable sustainability results (Sun *et al.* 2024).

Ultimately, firms' financing access is a realistic indicator of sustainability achievement (Wang *et al.* 2023). Viewed through the RBV and DCT lens, financing is a strategic resource that helps firms capture the competitive advantages of sustainability. Funding mobilizes ESG plans and converts them into tangible environmental and market benefits. Accordingly, we expect financing constraints to moderate the ESG–CGT relationship, such that higher(lower) constraints weaken(strengthen) the positive effect of ESG performance on an organization's transformation toward a low-carbon future. Consequently, this study's third hypothesis is as follows:

Hypothesis 3: Financing constraints moderate the positive influence of ESG performance on CGT.

Figure 1 presents the research framework, while the following sections develop the corresponding hypotheses. It highlights the direct relationship between ESG (Environmental, Social, and Governance) performance and Corporate Green Transformation (CGT), moderated by two critical contingency factors: Climate Risk (H2) and Financing Constraint (H3). This structure captures the complex interplay between external environmental pressure and internal resource limitations, reflecting the dual contingency approach adopted in this study. This framework aims to demonstrate how different ESG dimensions contribute to CGT under varying levels of climate risk and financial constraints, thereby providing a more nuanced understanding of sustainability transitions in corporate contexts.

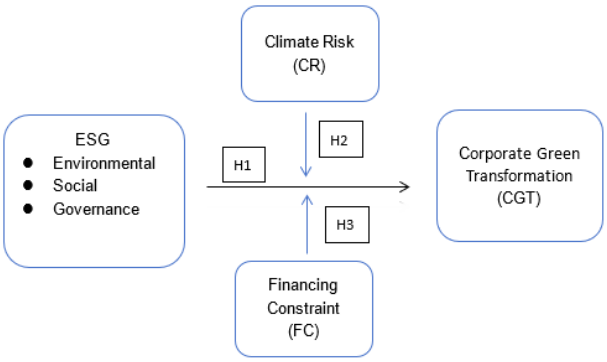


Figure 1. Research Framework

3. Methodology

3.1. Sample and Data Sources

This study explores the relationship between ESG performance and CGT via the moderating effects of climate risk and financing constraints. To achieve these objectives, we focused on a sample of Chinese listed companies, selected using two screening criteria: (1) firms with substantial missing data for ESG scores, CGT indicators, or climate-risk exposure were excluded; and (2) interpolation was used to solve any remaining missing values. The final sample comprised 12,306 firm-year observations from 2009 to 2023. The study period begins in 2009 because it marks the launch of ESG-related disclosure requirements and heightened global interest in corporate sustainability. Extending the dataset to 2023 provides the most recent and comprehensive data for assessing the interplay among ESG performance, CGT, climate risk, and financing constraints. The broad timeframe also enhances the sample's representativeness, capturing how ESG practices and climate risk management have evolved across various industries in China.

3.2. Measurement of Variables

3.2.1. Explained Variable (Y)

This study defines CGT as the process by which companies adopt greener practices, technologies, and strategies to reduce environmental impact and enhance sustainability.

To measure CGT, we referred to the works of Loughran and McDonald (2011) and Chen and Wu (2024), who performed textual analysis of listed firms' annual reports. This technique converts unstructured text from a company's annual report into a reliable quantitative proxy for its green transformation level.

Measuring CGT using textual analysis offers two advantages over traditional methods (e.g., principal component analysis, entropy, composite indicator models) or other proxies (e.g., green innovation). First, natural language processing tools enable the comprehensive evaluation of large-scale, unstructured data; this minimizes human error and enhances measurement reliability. Second, textual analysis encapsulates multiple components of green transformation (i.e., green cultural transformation, green strategic transformation, green innovation transformation, green investment transformation, green production transformation, and green emission transformation), reflecting the complete picture of CGT while addressing the shortcomings of single-indicator measures.

There are three main reasons for choosing the sample firms' annual reports as the data source for CGT. First, CGT-related information is usually disclosed in detail in these reports as part of corporate strategy. Second, annual reports are the most widely circulated and credible public documents of listed companies. Third, annual reports follow mandatory disclosure standards, and their uniform format and standardized language are well suited to keyword-based analysis. This ensures the efficient matching of keywords related to green transformation.

Figure 2. Keywords for CGT (Chen & Wu 2024)

Guided by policy documents such as the "Technical Guidelines for Assessing Corporate Environmental Behavior," the "White Paper on Green Manufacturing Standardization," and "Made in China 2025," we identified 113 keywords for CGT across five categories: strategic concepts, technological innovations, pollution control, publicity initiatives, and monitoring and management (see **Figure 2**). Using these keywords, we calculated their frequency of occurrence in the annual reports. Finally, the variables were expressed as the natural logarithm of the total word frequency plus one to adjust for data bias. This method provides a comprehensive and detailed understanding of CGT and aligns with the latest developments in text analysis techniques, thereby enhancing the reliability and validity of the explanatory variables.

3.2.2. Core Explanatory Variable (X)

Firms' ESG performance is increasingly under public scrutiny as a tangible indicator of sustainable development in the capital market, making it a significant component of business administration and operations (Tarmuji *et al.* 2016). ESG encourages the adoption of eco-friendly principles, including environmental stewardship, social responsibility and systematic governance, which align with today's low-carbon agenda. ESG scores by rating agencies are the main measures of a company's ESG performance (Conen & Hartmann 2019). The rating agencies derive those scores based on qualitative and quantitative assessments of firms' own ESG disclosures and third-party sources (Vannoni & Ciotti 2020).

For this study, we sourced Chinese listed companies' ESG data from Bloomberg (see https://www.bloombergchina.com/solution/sustainable-finance/). The Bloomberg ESG Disclosure Score evaluates how transparently and comprehensively a listed company reports on ESG matters, based on firms' publicly available documents (e.g., annual reports, sustainability reports). **Figure 3** depicts Bloomberg's indicator framework. Bloomberg's long-standing reputation in financial data provision ensures the accuracy and credibility of these measures.

Figure 3. ESG Assessment Indicator System (Bloomberg)

3.2.3. Moderating Variables

3.2.3.1 Climate Risk

To measure climate risk, we adopted the four-step integrated approach developed by Tang *et al*. (2024). First, annual reports for each sample firm were downloaded from the Juchao Information platform (http://www.cninfo.com.cn). Second, following Loughran and McDonald's (2011) dictionary method, we built an initial "climate risk" seed lexicon that drew from authoritative references such as the China Meteorological Hazards Yearbook and the National Weather Science Data Centre. The lexicon entries included generic climate-related phrases (e.g., "climate change," "extreme weather," "sea-level rise") as well as crisis-specific terms (e.g., "flood," "drought," "typhoon," "disaster loss," "disaster-affected area").

Third, we trained a natural language processing model as per Mikolov *et al*.'s (2013) neural network methodology to identify expressions semantically close to the seed

terms. This step expanded the lexicon to produce a more thorough, bias-free representation of climate risk discourse. Finally, we constructed the Climate Risk Exposure (CRE) index for each firm-year by calculating the percentage of lexicon term frequency from the total word count in the annual report. We then computed a three-year rolling average of weather indicators to account for short-lived disclosure fluctuations and gradual climate change. A higher CRE score denotes greater climate-related risk, which in this study is expected to affect the ESG-CGT connection.

3.2.3.2 Financing Constraints

Financing limitations greatly impede a firm's ability to acquire resources for strategic sustainability Financing constraints represent a critical barrier to corporate green transformation (CGT), as firms under tight liquidity face difficulties in committing sustained resources toward ESG investments. In this study, we follow Whited and Wu (2006) and adopt the Whited–Wu (WW) index to proxy firms' external financing constraints. The WW index is derived from a structural investment model and has been empirically validated as a more robust measure of financial frictions, especially in capital-intensive transformation scenarios (Hadlock & Pierce 2010; Whited & Wu 2006).

The WW index incorporates six accounting-based variables: cash flow, long-term debt, firm size, industry sales growth, and dividend payouts. Its formula is given as:

$$WW\ Index = -0.091 \times CashFlow / Total\ Assets - 0.062 \times Dividends / Total\ Assets + 0.021 \times Long-term Debt / Total\ Assets - 0.044 \times \log(Total\ Assets) - 0.102 \times Industry\ Sales\ Growth$$

Where:

CashFlow = Income Before Extraordinary Items + Total Depreciation and Amortization

Dividends = Total Cash Dividends Paid

Total Assets = Book value of total assets

Industry Sales Growth = Growth rate in sales for the firm's industry

A higher WW score indicates stronger financial constraints, i.e., the firm is more dependent on internal funds and faces greater difficulty accessing external capital markets. Conversely, lower WW values reflect firms with more financial flexibility, allowing them to engage more easily in green R&D, sustainability reporting, or carbon-reducing technology adoption.

This measure aligns better with our research context, where capital availability plays a moderating role in the ESG–CGT relationship. The WW index thus enhances our identification of how resource scarcity shapes ESG implementation effectiveness across firms.

3.2.4. Control Variables

This study also incorporated multiple control variables to isolate the specific impacts of ESG performance, climate risk, and financing constraints on CGT. Apart from the standard controls for firm size, leverage, and firm age, we introduced three potential confounding factors. First, internal control report disclosure signals firms' commitment to governance transparency, accountability, and social responsibility, which are known drivers of business sustainability (Chen *et al.* 2022; Kwilinski *et al.* 2023). This was treated as a dummy that equals '1' if the firm publishes an internal control disclosure report.

The second control variable is state ownership. Compared to private enterprises, state-controlled enterprises (SOEs) experience unique regulations and incentives for green transformation, aligning them with public policy and societal demands regarding sustainability. This makes SOEs more likely to assimilate green practices, whereas privately held firms may prioritize short-term financial returns over ESG (Dubash 2020; Ren *et al.* 2024; Xue *et al.* 2024).

Third, we included the number of overseas-educated board directors as a control variable. International exposure and cross-cultural learning can familiarize directors with global ESG best practices and climate strategies, increasing the likelihood that the firm adopts advanced green innovations (Li 2024; Chen *et al.* 2023). As such, firms with a higher number of foreign-educated directors may take more proactive decisions in responding to sustainability issues.

Including these comprehensive set of control variables ensured that the observed impacts of ESG, climate risk, and financing constraints were not confounded by firms' governance disclosure, ownership type, or board members' worldview, thus yielding more precise results on CGT.

3.3. Model Specification

Following Wang *et al*. (2023), Xie (2024) and Ao *et al*. (2023), we estimated a panel model to determine the direct effect of ESG on CGT, as well as the moderating influences of climate risk and financing constraints. Firm and year fixed effects were applied to curb omitted variable bias. **Table 1** lists the variables in the model estimation, while the empirical models are specified below.

3.3.1. Model 1 – Direct effect of ESG on CGT

Model 1 below tests whether a firm's ESG score explains the variation in CGT after accounting for the control variables. A positive and significant ESG coefficient would confirm that stronger ESG is associated with green transformation. To estimate the effect of ESG on CGT while mitigating omitted variable bias, we adopt a double-selection LASSO approach. Specifically, the selection procedure involves regressing both the dependent variable (CGT) and the treatment variable (ESG) on a comprehensive pool of potential controls that are predictive in either equation. The model structure can be expressed as:

$$CGT_{i,t} = \beta_0 + \theta ESG_{i,t} + \beta_2 CV_{i,t} + \varepsilon_{i,t}$$

where control variables are not manually specified but automatically selected via LASSO regressions based on

their predictive relevance for both the outcome (CGT) and the treatment (ESG).

3.3.2. Model 2: Climate risk as a contingency

The second model adds climate risk as moderator, incorporating the interaction term *ESG*CR* to measure the degree to which a high-risk climate alters the ESG-CGT link. If the interaction term's coefficient is significant, the moderating effect is considered present.

$$CGT_{i,t} = \beta_0 + \beta_1 ESG_{i,t} + \beta_2 CR_{i,t} + \beta_3 ESG * CR_{i,t} + \beta 4 CV_{i,t} + \varepsilon_{i,t}$$

3.3.3. Model 3: Financing constraints as a contingency

The third model assesses the moderating role of financing constraints, substituting the interaction term with *ESG*FC*. A significant interaction coefficient would show that the ESG–CGT relationship is stronger when financing is less constrained, indicating that financial flexibility is pivotal for ESG practices to drive sustainability transitions.

$$CGT_{i,t} = \beta_0 + \beta_1 ESG_{i,t} + \beta_2 FC_{i,t} + \beta_3 ESG * FC_{i,t} + \beta 4 CV_{i,t} + \varepsilon_{i,t}$$

Table 1. Variables Description

	Definition	Description	Abbreviations
Explained variable (Y)	Corporate green transformation	Corporate green transformationAbility	CGT
Core explanatory variable (X)	ESG performance	Corporate ESG Score	ESG
Moderating variables	Climate Risk	Corporate Climate Risk index	CR
	Financing Constraint	Corporate Financing constraint	FC
Control variables	Disclose the internal control evaluation report	Whether to disclose the internal control evaluation report	InternalControlDisclosure
	State-controlled	Whether it is state-controlled or not	State-controlled
	Directors with overseas education	Number of directors with overseas education	OverseasEducatedDirectors

Table 1 presents the descriptive statistics and variable definitions following data cleaning, providing a comprehensive overview of the dataset used for analysis. This table presents a detailed overview of the variables employed in this study, encompassing the dependent variable (Y), the primary independent variable (X), moderating variables, and control variables. A thorough understanding of the precise definitions and measurements of each variable is essential for conducting an accurate empirical analysis and achieving a robust interpretation of the model.

4. Empirical Results

4.1. Descriptive Statistics and Correlation Results

Descriptive analysis, correlation analysis, and multicollinearity analysis were conducted to ensure the robustness and reliability of the dataset for subsequent regression estimation.

Table 2 presents the descriptive statistics of the main variables. The average CGT is 1.83 with a standard deviation of 0.914, indicating moderate variation across observations. The three ESG pillars, Bloomberg-E, Bloomberg-S, and Bloomberg-G, have mean values of 8.681, 13.018, and 62.659, respectively, suggesting diverse environmental, social, and governance practices among firms. Climate risk has a low mean of 0.18 with significant variability (standard deviation = 0.229), whereas financing constraints have a high mean of -3.742 and low standard deviation of 0.366. Disclosure of internal control report has an average value of 0.102 (~10.2%), indicating that a minority of firms disclose internal control reports (per Table 2 means 0.1017), while state ownership's mean of 0.554 indicates that over half of the firms have government connections. Directors with overseas education shows an average of 0.744 with a maximum of nine, implying significant differences in the foreign education qualifications of firm boards.

Table 2. Descriptive Statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
CGT	12036	1.83	.914	0	5.606
E	12036	8.571	12.385	0	54.062
S	12036	13.200	7.910	0	38.483
G	12036	63.376	14.434	0	89.284
CR	12036	0.18	.229	0	3.478
FC	12036	-3.742	.366	-5.317	-0.664
InternalControlDisclosure	12036	0.1017	.302	0	1
State-controlled	12036	0.554	.497	0	1
OverseasEducatedDirectors	12036	0.744	1.114	0	9

Table 3 displays the pairwise correlations among the variables. CGT is positively correlated with E (0.364), S (0.310), and G (0.298), suggesting that improvements in ESG dimensions are associated with higher levels of CGT. The Climate Risk Index is also positively correlated with CGT (0.441), indicating that firms facing higher climate risks tend to engage more in green transformation. However, disclosure of internal control report has a negative correlation with CGT (-0.047), E (-0.180), and S (-0.284), suggesting that firms that disclose their internal control reports might exhibit less ESG. Other correlations are generally moderate, with no indication of overly strong linear relationships.

Table 4 provides the variance inflation factor (VIF) results to assess multicollinearity among the independent variables. Social and E exhibit the highest VIF values of 2.08 and 2.02, respectively, but remain well below the critical threshold of 10; therefore, they do not indicate multicollinearity. G, disclosure of internal control report, climate risk, directors with overseas education, and state ownership all have VIF values close to one, also eliminating multicollinearity concerns. Overall, the mean VIF of 1.38 confirms that multicollinearity is not an issue in the regression model.

Table 3. Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CGT	1.000							
E	0.364	1.000						
S	0.310	0.691	1.000					
G	0.298	0.449	0.466	1.000				
CR	0.441	0.167	0.144	0.155	1.000			
InternalControlDisclosure	-0.047	-0.180	-0.284	-0.305	-0.049	1.000		
State-controlled	0.059	0.013	0.018	-0.013	0.055	0.114	1.000	
OverseasEducatedDirectors	0.027	0.149	0.174	0.148	-0.050	-0.052	-0.022	1.000

Table 4. VIF test results

Variable	VIF	1/VIF
S	2.08	0.480536
E	2.02	0.49511
G	1.36	0.736049
InternalControlDisclosure	1.09	0.915931
CR	1.04	0.959886
FC	1.02	0.980535
OverseasEducatedDirectors	1.04	0.961721
State-controlled	1.02	0.98021
Mean VIF	1.38	

4.2. LASSO-Based Estimation Results

The results of the lasso regression are presented in **Table 5**, clarifying the relationship between the ESG pillars and CGT. The three models in the table represent the gradual addition of different predictors, yielding a comprehensive understanding of the mechanisms at play.

The results of the primary regression model using the double-selection LASSO approach are presented in **Table 5**, offering a data-driven perspective on the relationship between ESG performance and corporate green transformation (CGT). This method enhances model credibility by leveraging penalized regression to automatically select relevant control variables, thereby reducing omitted variable bias and improving estimation accuracy in high-dimensional contexts. The empirical findings indicate that ESG performance is a significant positive driver of CGT. Specifically, the coefficient for ESG is positive and statistically significant ($\beta = 0.0102$, $p < 0.01$), confirming that firms with higher ESG scores are more likely to engage in substantive green transition efforts. This result holds even after accounting for firm-level controls selected through the LASSO procedure. By using a machine learning-based variable selection strategy, the model improves robustness while mitigating risks of model overfitting or control variable misspecification.

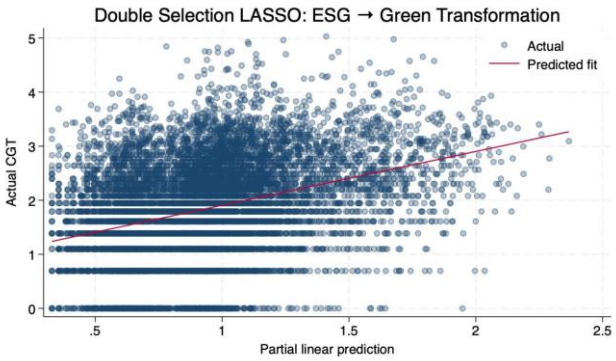


Figure 4. Lasso Regression

The graphical visualization in **Figure 4** further supports the model's effectiveness. The scatterplot of actual versus predicted CGT scores shows a clear upward trend, with predicted values aligning closely with observed data points. This reflects the LASSO model's capacity to capture the underlying structure of green transformation behavior among firms, reinforcing the predictive value of ESG performance in shaping sustainability strategies. In contrast to traditional OLS-based specifications that rely

on fixed or manually selected controls, the LASSO method provides a more flexible and objective control selection process, ensuring that only covariates with meaningful explanatory power are retained. As a result, the estimated effect of ESG is not only statistically robust but also substantively meaningful in practical terms.

Overall, the empirical findings strongly support Hypothesis 1, illustrating that ESG performance significantly enhances CGT. The results offer valuable empirical insights for policymakers and corporate leaders, particularly regarding the necessity for comprehensive ESG practices as strategic tools for sustainable business development and environmental resilience.

Table 5. Lasso regression

Variable	Coefficient	z-value	p-value
ESG	0.0102***		
(0.0011)	9.27	0.000	
Constant	0.5825***		
(0.0550)	10.59	0.000	
Year FE	Yes		
Region FE	Yes		
Observations	12,036		
R^2	0.254		

Note: The table reports the double-selection LASSO estimation results for the effect of Bloomberg ESG score on the Corporate Green Transformation (CGT) index. Standard errors are in parentheses. Year and region fixed effects are included. *, *, * denote significance at the 1%, 5%, and 10% levels, respectively.*

Table 6. Moderating effect results of CR

Variable	(1)	(2)	(3)
E	**0.0124*** (0.0013)**	0.0096*** (0.0011)	0.0095*** (0.0011)
S	0.0107*** (0.0018)	**0.0176*** (0.0022)**	0.0105*** (0.0018)
G	0.0085*** (0.0008)	0.0082*** (0.0008)	**0.0114*** (0.0010)**
CR	2.5816*** (0.2557)	3.0042*** (0.2941)	3.5915*** (0.4450)
E_CR	**-0.0142*** (0.0042)**		
S_CR		**-0.0363*** (0.0068)**	
G_CR			**-0.0175*** (0.0048)**
Disclose the internal control evaluation report	0.3199*** (0.0339)	0.3227*** (0.0337)	0.3161*** (0.0338)
State-controlled	0.0195 (0.0649)	0.0158 (0.0635)	0.0214 (0.0644)
OverseasEducatedDirectors	-0.0075 (0.0149)	-0.0091 (0.0149)	-0.0087 (0.0149)
Cons	0.2537*** (0.0772)	0.1954** (0.0778)	0.1010 (0.0892)
Year FE	Yes	Yes	Yes
Region FE	Yes	Yes	Yes
Obs	12,036	12,036	12,036
R2	0.314	0.317	0.315

4.3. Moderation Analysis of Climate Risk

The results presented in **Table 6** reveal the dynamic ESG-CGT link when climate risk is introduced as a moderating variable. Columns (1) through (3) progressively illustrate how climate risk subtly influences the positive relationship between each ESG dimension and CGT. A positive coefficient for the interaction term indicates that firms facing higher climate risk are more likely to prioritize and strengthen their ESG practices, driving substantial progress in green transformation. On the other hand, a negative coefficient implies that increased exposure to climate risk hinders the effectiveness of ESG initiatives, potentially due to greater financial pressures or operational constraints; in turn, the firm's ability to transition to sustainable practices is slowed down.

In Column (1), the interaction term between the environmental pillar of ESG and climate risk produces a significant yet unexpectedly negative moderating effect ($\beta = -0.0142$, $p < 0.01$). We find that firms facing greater climate risk are less willing to leverage environmental performance for green transformation. This unforeseen outcome suggests that, under increased climate risk, firms may reallocate resources typically designated for proactive environmental initiatives, channeling them instead to urgent risk mitigation strategies (Ren *et al.* 2024; Chen *et al.* 2024).

As presented in Column (2), the social pillar of ESG yields a surprising result as well. The positive effect of social responsibility on CGT appears to decrease sharply when climate risk is factored in ($\beta = -0.0363$, $p < 0.01$). Potentially, heightened pressure from climate risk forces firms to deprioritize social responsibility investments, viewing them as less immediately beneficial compared to direct economic profits (Zhang *et al.* 2024; Li 2024).

A similar yet less pronounced result is observed in Column (3) for the governance dimension of ESG. Its positive effect on CGT diminishes in the presence of climate risk, suggesting that even firms with strong governance structures may struggle to swiftly mobilize decision-making processes in response to escalating climate

threats (Xi & Wang 2024; Yuan *et al.* 2024). In summary, the significant interaction terms confirm that climate risk plays a critical moderating role in weakening the relationship between ESG performance and CGT.

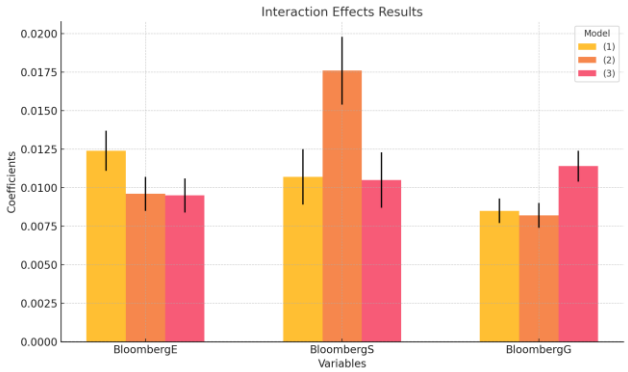


Figure 5. Moderating Effect Of CR On ESG Dimensions

Figure 5 illustrates the moderating interaction of climate risk with the dimensions of ESG performance. The results reveal notable variations in coefficient estimates, as represented by the three color-coded bars. The inclusion of error bars further highlights the statistical uncertainty associated with these estimates. A key observation is that the social dimension exhibits the most pronounced moderating effect of climate risk, particularly in Model 1 (orange) where it significantly surpasses the estimates in Models 2 and 3. The implication is that when climate uncertainty rises in the external environment, firms' social responsibility initiatives (e.g., labor practices, community engagement, stakeholder relations) become the most vulnerable. By contrast, the relatively stable coefficients of the environmental and governance pillars imply less volatility in the face of immediate climate shocks, as these activities are embedded in longer-term policies and compliance structures.

4.4. Moderation Analysis of Financing Constraints

The results in **Table 7** examine the moderating role of financing constraints on the relationship between ESG dimensions (environmental, social, and governance) and CGT. A positive coefficient implies that firms with fewer financial barriers can leverage ESG investments more effectively, accelerating their green transition. In contrast, a negative coefficient indicates that constrained financial access undermines the potential benefits of ESG efforts, stifling green innovation and sustainability-driven restructuring.

As shown in Column 1, the interaction term between the environmental pillar of ESG and financing constraints is positive and statistically significant (β = 0.00796, p<0.01), indicating that financing constraints strengthen the positive impact of environmental performance on CGT. Similarly, Column 2 and Column 3 support the significant moderating effect of financial constraints on the impacts of the social (β = 0.0156, p<0.01) and governance (β = –0.000188, p<0.01) dimensions on CGT, respectively. Notably, limited financing enhances the effect of social responsibility on green transformation, but slightly weakens the effect of strong governance. In summary, the statistically significant coefficients of the interaction terms suggest that financing constraints exert a tangible influence on the ESG-CGT relationship.

Table 7. Moderation Analysis Results for Financing Constraints (ww index)

Variables	(1)	(2)	(3)
E	**-0.0271***(0.0096)**	0.0040***(0.0013)	0.0041***(0.0013)
S	0.0087***(0.0020)	**0.0094***(0.0020)**	0.0010***(0.0002)
G	0.0012(0.0013)	0.000974(0.452)	**0.0094***(0.0016)**
FC (WW_index)	0.0010***(0.0001)	0.00103(0.295)	0.00388***(0.0287)
E_FC	**-0.0278***(0.0086)**		
S_FC		**-0.0058***(0.0055)**	
G_FC			**-0.0010***(0.0008)**
InternalControlDisclosure	0.2803***(0.0382)	0.0432(0.545)	0.346***(0.0215)
State-controlled	0.0459***(0.0115)	0.0835***(0.0276)	0.0817***(0.0276)
Directors with overseas education	-0.0167***(0.0111)	-0.00654(0.110)	-0.0180(0.0113)
Cons	1.3198***(0.1060)	1.3244***(0.1063)	1.3664***(0.1112)
Year FE	Yes	Yes	Yes
Region FE	Yes	Yes	Yes
Obs	12,036	12,036	12,036
R2	0.6369	0.6361	0.6361

As visualized in **Figure 6**, the moderation effect of financing constraints in relation to the environmental and social pillars of ESG expands as funding becomes easier. Put differently, firms with slack resources can turn environmental upgrades and social programs into concrete sustainability gains more readily. For the governance pillar, the negative interaction term indicates that governance mechanisms matter most when money is tight. Under financial stress, strong boards, risk-control systems and internal monitoring appear to substitute scarce capital by safeguarding efficiency and compliance. Together, these patterns underscore that financing constraints moderate ESG dimensions in heterogeneous ways—positive for environmental and social activities, but negative for governance activities—implying that managers should calibrate their ESG focus to the firm's

financial latitude if they want to maximize sustainability performance.

4.5. Robustness Check Results

To verify that our main findings are reliable and not results of endogeneity or model misspecification, we conducted robustness testing using the two-step system Generalized Method of Moments (GMM) estimator. GMM is an effective technique for addressing potential endogeneity stemming from issues like unobserved heterogeneity, autocorrelation, heteroskedasticity, and reverse causality. **Table 8** presents the results of the GMM estimation.

In our lasso regression, the lagged values of ESG scores and climate risk were confirmed to be valid instruments. The Hansen J-statistic test for over-identifying restrictions also supported that these instruments are relevant, exogenous, and uncorrelated with residuals. Thus, the model does not involve any overfitting. Additionally, the Arellano–Bond test for autocorrelation detected no second-order serial correlation in the differenced residuals, verifying that our instruments are indeed exogenous, valid, and consistent in estimation. This result proves the suitability of the GMM approach for the dataset. Moreover, this study verify the robustness of our main findings by using two alternative proxies for green transformation that better capture the economic substance and potential biases in ESG performance: (1) a Greenwashing Index and (2) a Green Innovation Bubble Index.

As reported in **Table 9**, the ESG indicators—particularly the Environmental and Social dimensions—show no statistically significant association with these alternative proxies. This lack of significance supports our claim that the original ESG–CGT relationship is not driven by disclosure inflation, greenwashing, or ESG hype cycles, which would have otherwise shown strong associations in these models. In other words, firms with strong ESG profiles are not merely engaging in symbolic environmental behavior, lending credibility to the construct validity of our CGT measure.

Subsequently, we tested for sensitivity by altering the instruments and model specifications. Across all variants, the moderating roles of climate risk and financing constraints remain statistically significant and stable in the ESG-CGT nexus.

Table 8. GMM results

Variables	Model 1	Model 2 (CR)	Model 3 (FC)
L. CGT	0.55718***(0.01748)	0.55718***(0.01748)	0.6583***(0.0000)
E	0.00856***(0.00107)	0.00893*** (0.01811)	-0.0326*** (0.0116)
S	0.00339(0.00206)	0.0276*** (0.0022)	0.02806*** (0.005)
G	0.00797***(0.00082)	0.0192*** (0.0008)	0.0665*** (0.0015)
CR		3.0042*** (0.2941)	
FC			-0.0904 (0.759)
E_M		**-0.0142*** (0.0042)**	**-0.00879***(0.0064)**
S_M		**-0.0363*** (0.0068)**	**-0.0571***(0.0297)**
G_M		**-0.0175*** (0.0048)**	**-0.07577***(0.0025)**
InternalControlDisclosure	0.1244***(0.03688)	0.3227*** (0.0337)	0.1935*** (0.0071)
State-controlled	0.01257(0.02161)	0.0158 (0.0635)	0.0084 (0.134)
OverseasEducatedDirectors	-0.01727(0.00886)	-0.0091 (0.0149)	-0.0133 (0.0149)
Cons	0.11195(0.0714834)	0.1954** (0.0778)	0.426 (0.0892)
AR(1)	0.014	0.020	0.016
Sargan Test	chi2(11) = 12.34, p-value = 0.287	chi2(11) = 11.25, p-value = 0.314	chi2(11) = 19.51, p-value = 0.894

Table 9. Robustness Check: Alternative Measures of CGT

Variables	(1) Wash-Green	(2) Green Innovation Bubble
E	0.00263*** (0.00073)	-0.00270 (0.00233)
S	-0.00158 (0.00119)	-0.00302 (0.00344)
G	0.00087 (0.00064)	0.00008 (0.00243)
OverseasEducatedDirectors	0.00620 (0.00630)	-0.02936 (0.04905)
InternalControlDisclosure	0.00963 (0.01592)	0.12162 (0.08964)
State-controlled	0.02199 (0.03941)	0.07168** (0.03627)
Cons	0.17732*** (0.04994)	0.03461 (0.18371)
Year FE	Yes	Yes
Region FE	Yes	Yes
Obs	10,688	11,457
R^2	0.4821	0.4471

Overall, the GMM results not only addressed potential endogeneity concerns but also built confidence in the robustness of our results. The consistent findings across various diagnostic checks and model specifications

suggest that the relationships among climate risk, financing constraints, ESG performance, and CGT are indeed reliable, reflecting true underlying patterns rather than omitted variables or measurement errors.

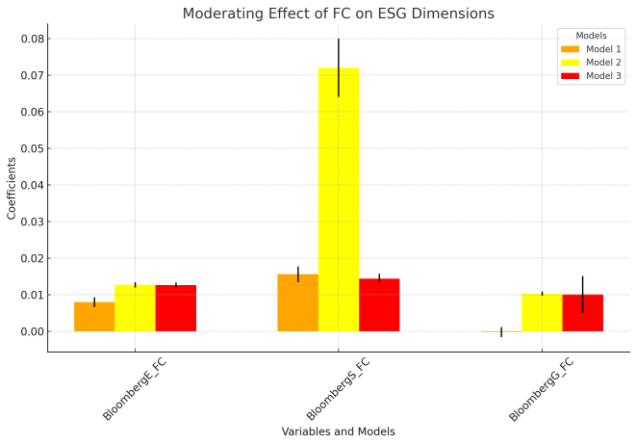


Figure 6. Moderating Effect of FC On ESG Dimensions

4.6. Marginal Analysis Results

Figure 6 plots the incremental contribution of each ESG pillar over five ascending levels of climate risk. All three slopes trend downward, indicating a significant negative moderation effect of climate risk. The marginal effect of ESG on CGT declines with increasing levels of climate risk. The environmental dimension, for instance, falls from roughly 0.012 at the lowest risk level to about 0.006 at the highest—a trend also observed in the social and governance dimensions. The steepest decline appears in the social pillar, suggesting that social responsibility programs are particularly sensitive to climate-driven threats. In short, elevated climate risk materially weakens the ability of ESG performance to drive green transformation gains, highlighting the value of a stable operating environment for firms seeking to maximize ESG returns.

These results also point to an uneven climate risk response within ESG. The social pillar adjusts most dynamically, giving rise to new questions about what propels firms to recalibrate their ESG priorities under climate uncertainty. Future work could examine whether stricter regulation, changing stakeholder demands, or evolving sustainable-investment criteria explain this heightened sensitivity. Clarifying those mechanisms would help managers calibrate ESG strategies more effectively when climate volatility looms.

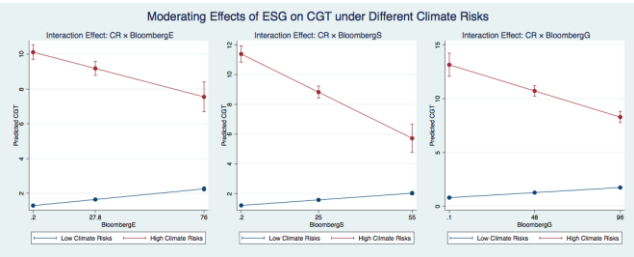


Figure 7. Moderating Effect Of CR

4.6.1. Nonlinear Robustness Using Causal Forest Estimation

To complement the linear interaction models and further investigate the heterogeneous impact of ESG performance across varying levels of climate risk, we implement a Causal Forest estimator. This machine learning approach allows for a nonparametric estimation of treatment effects conditional on moderators, capturing complex, nonlinear interactions that may be overlooked in traditional regression frameworks.

Figure 8 plots the estimated marginal treatment effect of ESG on corporate green transformation across the full spectrum of climate risk scores. A distinct inverted U-shaped pattern emerges: ESG effectiveness rises with increasing climate risk at first, peaking around moderate risk levels, but subsequently declines as climate risk intensifies. This suggests that while ESG initiatives initially help firms adapt to moderate climate threats, their marginal contribution diminishes under extreme risk conditions—possibly due to overstretched capacities or rising systemic constraints.

These nonlinear findings are consistent with our benchmark regression results (**Figure 7**), yet offer more granular insights into how ESG efficacy varies continuously with environmental volatility. This robustness check reinforces the credibility of our core conclusions and highlights the added value of machine learning in uncovering context-dependent ESG dynamics.

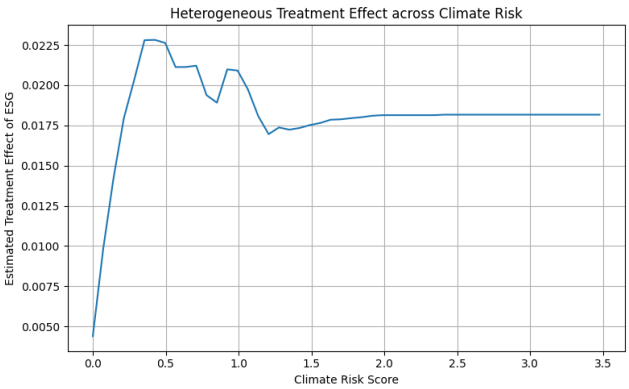


Figure 8. Nonlinear Moderation of Climate Risk on ESG Effects

Figure 9 depicts how the marginal influence of each ESG dimension changes as financing constraints tighten or loosen. Two clear patterns emerge. First, the marginal influence of environmental and social dimensions on CGT strengthens when financing constraints are relaxed. Firms with greater financial slack can more effectively transform environmental upgrades and social commitments into tangible green outcomes. This suggests that capital abundance enhances the conversion efficiency of ESG investments into sustainable transformation. Second, the governance pillar likewise shows a stronger positive marginal effect on CGT under low financing constraints, albeit to a lesser extent. This diverges from prior expectations that governance becomes more critical under financial stress. Instead, the pattern indicates that sound governance complements environmental and social efforts best when firms have sufficient capital to act upon strategic decisions. Third, across all dimensions, firms facing high financing constraints consistently exhibit

flatter ESG–CGT slopes, underscoring a general dampening effect of capital tightness on the returns to ESG engagement. The results highlight that financial slack not only facilitates ESG implementation but also enhances its payoff in driving green transformation.

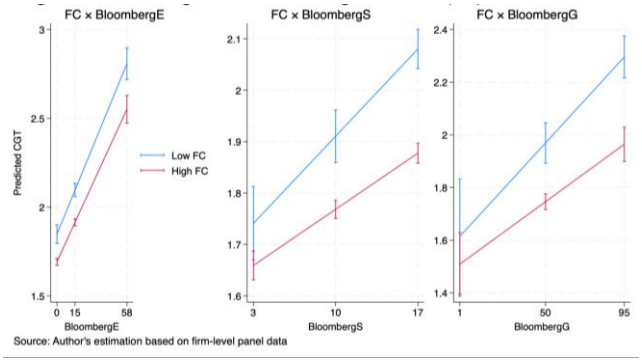


Figure 9. Moderating Effect of FC On ESG Dimensions

Overall, the results underscore how financial constraints affect the different components of ESG performance unequally, with the social aspect being the most sensitive. This observation prompts further inquiry into whether firms under financial strain are deliberately shifting resources toward social initiatives as a way to manage reputational concerns, or whether such emphasis is a response to external pressures from regulators and investors that disproportionately influence ESG priorities. Future studies may examine the underlying drivers of this trend, focusing on how external financing environments and investor expectations shape ESG-related decisions when firms face limited financial flexibility.

4.7. Explaining ESG–Green Transformation Mechanism via SHAP Analysis

Leveraging SHAP value decomposition from an XGBoost model, we dissect the marginal impact of ESG subcomponents on green transformation at the firm level. **Figure 10** presents the SHAP summary plot, which illustrates both the distribution and directional impact of ESG components on firm-level green transformation. The color gradient denotes the relative feature values across observations, ranging from low (blue) to high (red), while the SHAP values along the x-axis capture the marginal contribution of each ESG dimension to the predicted outcome. Three key insights emerge from the analysis. First, the environmental pillar demonstrates the highest marginal influence, with a mean SHAP gain of 2.63. This highlights the pivotal role of environmental responsibility and green technological investment in driving substantive transformation. Second, governance ranks next (1.58), emphasizing the importance of internal controls, strategic alignment, and transparency in fostering sustainable development. Third, the social dimension, with the lowest gain (1.28), appears to exert a more indirect or delayed effect on measurable green outcomes. The model's Mean Squared Error (MSE) stands at 0.6337, suggesting a good overall fit and reliable predictive capacity.

Taken together, these results underscore the heterogeneous influence of ESG components and provide empirical evidence that environmental and governance dimensions carry greater explanatory power in advancing corporate green transformation. Compared to conventional linear models, the SHAP approach offers more nuanced insights into nonlinear relationships and heterogeneous marginal effects, aligning with the economic rationale underpinning environmental investment theory. The relatively modest impact of the social dimension may reflect its longer-term orientation or lower short-term return on investment relative to environmental initiatives.

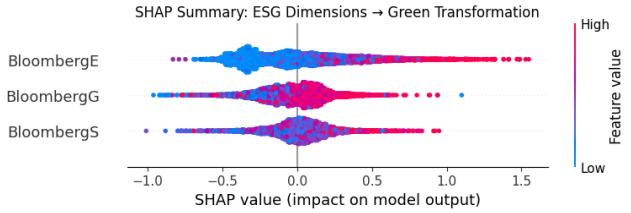


Figure 10 . SHAP-Based Mechanism Analysis

Table 10. Feature Importance by Gain

Feature	Gain
BloombergE	2.63
BloombergG	1.58
BloombergS	1.28

4.8. Heterogeneity analysis

To further explore heterogeneity analysis in the ESG–green transformation relationship, this study compute SHAP interaction values between each ESG pillar and the climate risk index. **Figure 11** illustrates the regional average of these interaction effects, highlighting how climate risk conditions differentially shape the marginal contributions of ESG components across provinces.

Three key findings emerge. First, the Governance × Climate Risk interaction (BloombergG_CR) exhibits the highest explanatory power across all regions, particularly in the western and central provinces. This suggests that institutional transparency and strategic foresight become increasingly valuable under uncertain climate conditions, enabling firms to better adapt to environmental volatility. Second, the Social × CR and Environmental × CR effects are more modest but remain stable across regions, indicating that their marginal gains are less sensitive to climate risk heterogeneity.

These results lend empirical support to the contingency view of ESG effectiveness, affirming that climate risk not only acts as an external constraint but also reconfigures the internal value relevance of ESG capabilities. This mechanism enriches the main effect findings and helps address reviewer concerns regarding the robustness of climate risk measurement.

To deepen the understanding of how financial constraints shape the ESG–green transformation relationship, this study incorporates interaction terms between ESG dimensions and a financing constraint proxy. **Figure 12** presents the regional averages of these ESG × FC interaction values, revealing significant heterogeneity across China's provinces. The results show that the Governance × Financing Constraint interaction exhibits

the strongest negative contribution across all regions, especially in the western and central provinces. This indicates that under capital pressure, the role of governance in facilitating green transformation becomes particularly pronounced. Meanwhile, the interaction effects of Environmental and Social dimensions are relatively weaker, though still negative, suggesting that limited financing uniformly suppresses the effectiveness of ESG efforts. These findings underscore the moderating role of financing constraints in shaping ESG's contribution to sustainable corporate transition.

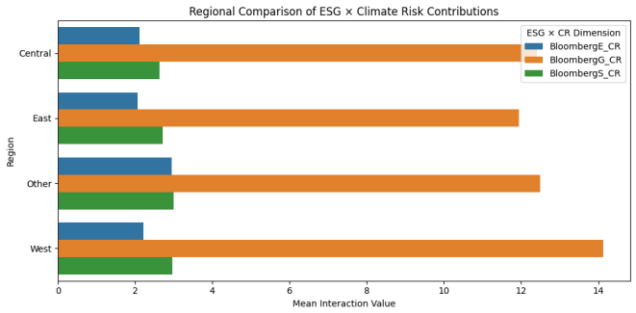


Figure 11. Regional Comparison of ESG × Climate Risk Interaction Contributions to Green Transformation

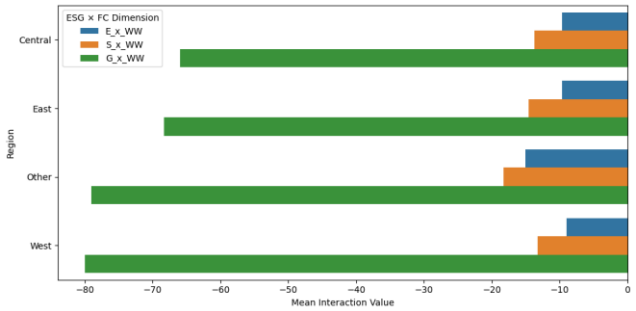


Figure 12. Regional Comparison of ESG × Financing Constraint Interaction Contributions to Green Transformation

While endogeneity is a major concern in observational ESG research, our study addresses this through a multi-pronged strategy: System GMM to control for reverse causality, Double Lasso to select theoretically consistent covariates, and SHAP-based machine learning to uncover non-linear impact structures. These combined strategies enhance the credibility of our findings and reinforce the argument that ESG effects on green transformation are both robust and context-dependent.

5. Discussion

This investigation adopted an integrated theoretical lens of the RBV, DCT, and Contingency Theory to evaluate how ESG performance propels CGT in the face of two contingencies: climate risk and financing constraints. Drawing on a panel of Chinese listed firms from 2009 to 2023, we constructed the main variables (i.e., ESG, CGT, climate risk, financing constraints) with text-mining techniques, Bloomberg ESG scores, and the WW index. The lasso regression and GMM estimation, supplemented by extensive robustness checks, reveal the climate risk levels and financing conditions under which the three ESG pillars foster green transformation. In addition, environmental externality theory further explains how ESG efforts—particularly in the environmental pillar—internalize the social costs of pollution, thereby legitimizing firm-level sustainability transitions. By unpacking these moderating effects across the three ESG pillars, we gain a clearer picture of why organizations make decisions when climate uncertainty and financial limitations collide. These insights inform both managerial strategy and public policy.

5.1. ESG under Climate Risk: A Potent Moderator

Our analysis shows that climate risk is a powerful condition to which ESG efforts are bound when pursuing CGT. Firms with high climate exposure typically focus on the environmental and governance pillars, echoing Qing *et al.*'s (2024) argument that ecological pressure can stimulate (not inhibit) innovation. That is, the greater the climatic threat, the more a firm relies on rigorous governance and targeted environmental practices to advance its green agenda. These companies are motivated by the need to ensure long-term sustainability by reducing environmental damage and avoiding the financial and reputational repercussions of non-compliance. As climate-related risks intensify, firms increasingly view sustainability as a strategic advantage (Tang *et al.* 2024; Lei & Xu 2024a). This is consistent with environmental externality theory, which posits that firms internalize the cost of pollution when facing strong ecological constraints, thus aligning private strategies with public environmental goals. By proactively managing climate risks, they not only meet regulatory requirements but also gain a competitive edge by improving their environmental performance (Zhang *et al.* 2025; Lin *et al.* 2024; Lei & Xu 2024b).

However, this study found a weaker association between the social dimension and overall ESG performance, raising the question: why does social responsibility take a backseat to climate risk? One explanation may lie in the short-term orientation of many firms. While governance and environmental policies are prioritized due to legal obligations and market-driven incentives, social initiatives (e.g., labor rights and community engagement) often require longer timeframes to show tangible outcomes and typically attract less immediate attention. This tendency is supported by Resource Dependency Theory, which argues that organizations focus on securing resources critical to their immediate survival (Pfeffer & Salancik 1978). As a result, companies may concentrate on regulatory and environmental compliance to quickly respond to external pressures, while social factors are deprioritized unless they pose direct financial or reputational risks. This finding is further corroborated by SHAP-based interaction analysis, which reveals that the marginal contribution of the social dimension significantly declines as climate risk intensifies. The nonlinear pattern in results reinforces the notion that climate uncertainty selectively attenuates ESG effectiveness, especially in areas with delayed or intangible payoffs.

5.2. ESG under Financing Constraints: The Need for Financial Incentives

Limited access to capital affects more than just a firm's investment capacity; it also shapes how extensively and how quickly ESG initiatives are rolled out. Our refined empirical approach sheds light on the financial dynamics underlying corporate sustainability. Ultimately, the effectiveness of ESG strategies in driving meaningful environmental outcomes appears closely tied to a firm's financial robustness. This study suggests that financial constraints significantly influence which ESG dimensions companies prioritize, especially when climate risk is a factor. Firms operating under tight budgets are often reluctant to commit to green initiatives that require long-term investments. This aligns with Agency Theory, which argues that managers, acting on behalf of shareholders, may prioritize short-term financial performance over long-term sustainability to satisfy immediate investor expectations (Jensen & Meckling 1976). This phenomenon also resonates with the concept of capital market imperfections in environmental economics, where liquidity constraints distort firms' optimal environmental investment decisions (Whited & Wu 2006; Hadlock & Pierce 2010).

The situation becomes even more complex when both climate risk and financial pressure come into play. Companies are frequently caught between pursuing immediate profitability and securing long-term resilience. In this context, digital transformation can offer a cost-effective pathway to environmental progress. Firms can harness digital tools for emissions management and green innovation, enabling ESG advancement without the need for substantial upfront spending. This supports the argument made by Kwilinski, Lyulyov, and Pimonenko (2023), who found that digital adoption can lower the costs of sustainable operations by streamlining processes. Consistent with this logic, our SHAP-based interaction analysis (**Figure 11**) shows that the marginal contribution of governance to green transformation drops sharply as financial constraints increase – highlighting a critical nonlinear threshold beyond which ESG effectiveness deteriorates.

Additionally, in industries where short-term returns are prioritized, financial limitations often push firms to focus more on environmental metrics than on social or governance commitments. The growing availability of green financing has created an incentive for companies to adopt ESG policies, particularly to gain access to favorable loan terms and investment options. However, despite the variety of funding avenues available, firms are often forced to choose between investing in environmental technology and allocating resources to social or governance practices, which are areas frequently sidelined (Chen *et al.* 2022). This selective allocation reflects a cost-benefit logic consistent with environmental investment theory, whereby firms under budget constraints prioritize ESG activities with immediate payoffs or direct access to capital incentives.

5.3. Reconciling Climate Risk, Financing, and ESG for CGT Achievement

The synergetic interaction between climate risk and financial constraints in shaping ESG performance is complex. The results indicate that when companies face climate-related pressures, they tend to prioritize environmental and governance initiatives. However, this often comes at the cost of social programs, unless reinforced by strong regulatory frameworks or heightened consumer expectations. This trade-off is plausible; under financial strain, firms are likely to favor actions that align closely with risk mitigation or cost reduction, rather than long-term or intangible benefits. This is further supported by empirical findings: SHAP-based interaction values show that the marginal effect of ESG, particularly the governance pillar, weakens considerably under dual exposure to climate risk and capital constraints, reinforcing the idea that firms adjust ESG priorities under multidimensional pressure.

Digital transformation, however, may offer a practical solution to this dilemma. Technologies such as smart carbon management systems and blockchain-based resource tracking enable firms to enhance environmental outcomes with minimal capital outlay. These innovations can reduce operational inefficiencies while supporting sustainability goals, making them especially attractive to firms with limited financial flexibility. This view is consistent with Sun *et al*. (2024), who argue that digital advancements can spur green innovation and make ESG implementation more attainable for cash-constrained enterprises.

Given this, a more refined perspective on sustainability strategy is needed to reflect the complexity of navigating compound external pressures, including both climate risks and capital constraints. Companies must adopt a strategic mindset that weighs short-term constraints against long-term imperatives, especially in today's increasingly eco-aware business environment (Lin *et al.* 2024; Chen *et al.* 2025). Integrated approaches that leverage digital tools for environmental and governance gains, combined with targeted financial incentives such as tax breaks or access to green capital, can help firms strengthen their ESG portfolios more evenly (Jin *et al.* 2023; Lei & He 2025). Integrated approaches that combine digital solutions, green financing channels, and ESG governance mechanisms can help firms strengthen their ESG portfolios more evenly and adaptively.

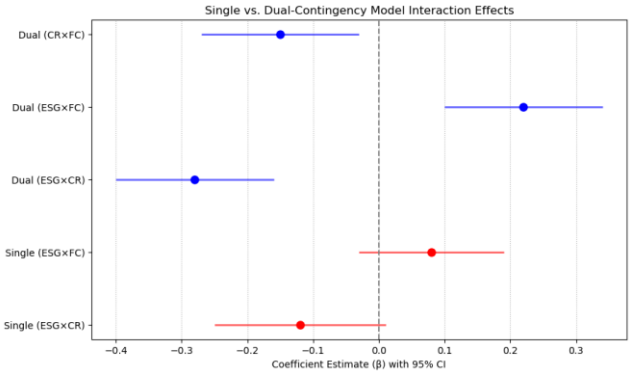


Figure 13. Comparison of Single vs. Dual-Contingency Interaction Effects

In summary, while climate risk tends to accelerate environmental and governance responses, financing constraints continue to shape the scope and depth of ESG actions. These asymmetric effects, further confirmed by the interaction coefficients shown in **Figure 13**, highlight the importance of jointly considering multiple contingencies when designing ESG strategies. Policymakers and business leaders must work together to foster conditions where digital innovation and green finance ease the burden on firms. Only by doing so can companies reconcile immediate financial pressures with broader sustainability commitments and move forward confidently in their green transformation journeys.

6. Conclusion, Implications, and Future Research

This study sheds light on how climate-related risks and financial constraints jointly shape ESG outcomes across its three pillars, following the technical roadmap depicted in **Figure 8**. The evidence suggests that when climate risks intensify, companies are more likely to prioritize environmental action and governance enhancements, while placing comparatively less focus on social dimensions. This trend aligns with observations by Tang, Gao, and Zhou (2024), who noted that firms under environmental stress tend to respond with strengthened governance and sustainability practices due to regulatory and market pressures. Chen *et al*. (2022) also pointed out that while social considerations are important, they are frequently overshadowed by the more immediate and measurable demands tied to environmental and governance obligations.

The combination of limited funding and climate risk presents a difficult scenario for firms, forcing them to choose between short-term financial health and long-term sustainability planning. Agency Theory (Jensen & Meckling 1976) offers a useful lens here, suggesting that managers, tasked with meeting shareholder expectations, may prioritize near-term gains at the expense of future-oriented ESG investments. Digital tools may help mitigate this dilemma. Research by Sun *et al*. (2024) highlights how adopting digital solutions can reduce ESG implementation costs, allowing firms to meet sustainability goals without straining financial resources. Similarly, Kwilinski, Lyulyov, and Pimonenko (2023) argue that such technologies improve operational efficiency, offering a cost-effective pathway to greener outcomes.

Firms with constrained access to capital often concentrate on environmental aspects, sidelining governance and social efforts, especially in industries driven by immediate financial performance. The growing availability of green finance, however, has shifted some incentives. Higher ESG ratings can lower borrowing costs and grant access to environmentally linked investments (Wang *et al.* 2023). Nonetheless, as Chen *et al*. (2022) observed, even with new funding options, companies often prioritize green technology over social or governance commitments, viewing the latter as secondary in terms of return on investment. This issue is compounded by the "green premium," which tends to benefit larger companies disproportionately, deepening inequalities in how different firms address climate challenges (Li 2024).

Our results suggest that climate risk does more than influence ESG performance in isolation; it interacts meaningfully with financing limitations, making implementation even more complex. The study offers a refined empirical framework that highlights financial resilience as a critical enabler for sustainability. Without it, companies are less equipped to manage the transition to environmentally responsible practices. This finding echoes the argument made by Porter and Van Der Linde (1995), who proposed that environmental constraints, while challenging at first, can lead to innovation and long-term economic benefits when firms are strategically and financially prepared.

Based on these findings, several practical recommendations emerge. Firms should emphasize governance and environmental actions in response to growing regulatory and market scrutiny around climate issues. Strengthening financial resilience through technology adoption (e.g., smart emissions tracking or automation) can help firms pursue ESG goals without high upfront investments. As Sun *et al*. (2024) note, leveraging digital systems can drive sustainability improvements even under tight budgets. Companies should also explore green finance tools like green bonds or climate-linked financial instruments to ease funding challenges and unlock capital for environmental upgrades.

Importantly, the social component of ESG should not be neglected. Even though it appears less directly impacted by climate risk, social responsibility—ranging from employee rights to community outreach—should be integrated into broader ESG strategies. Xie (2024) emphasizes that blending social objectives with governance and environmental goals can enhance competitive advantage, especially as markets increasingly reward holistic sustainability.

Policymakers have a crucial role as well. They must develop financial and regulatory ecosystems that empower firms to overcome capital constraints while embracing sustainability. Instruments like tax incentives, green bond support, and differentiated carbon policies can help reduce barriers to ESG adoption. Compared to direct subsidies, market-based tools such as green bonds and carbon pricing tend to enhance allocative efficiency while reducing regulatory distortion. Encouraging firms to assess and disclose their climate risk exposure, in line with the TCFD recommendations, will further enhance transparency and preparedness. Sector-specific regulatory frameworks—such as targeted subsidies for green innovation or carbon credit mechanisms—can ensure that companies across industries have tailored pathways to ESG integration. Such tools, when designed based on cost-benefit and marginal abatement principles, are more likely to stimulate dynamic efficiency and innovation. Aligning these efforts with global standards like the EU's Carbon Border Adjustment Mechanism will also help promote regulatory consistency and global competitiveness (Vannoni & Ciotti 2020).

This study opens several avenues for further exploration, particularly in understanding how climate risk and financial constraints jointly affect ESG performance across different sectors. Future research could delve deeper into how digital technologies facilitate green innovation and influence how firms, depending on industry and risk exposure, allocate focus among ESG priorities. There is also a pressing need to investigate the social dimension more thoroughly, identifying strategies to better embed social sustainability into corporate agendas alongside environmental and governance goals. One limitation of this study lies in the measurement of climate risk. The current proxy—based on the frequency of climate-related terms in corporate disclosures — captures firms ' perceived or reported risk exposure rather than objective, realized physical or transition risks. While this approach aligns with literature on disclosure-based climate risk assessment, it may be influenced by strategic reporting behavior and does not fully reflect the economic consequences of climate threats. Future research could improve this measure by incorporating geospatial climate data, carbon emission intensity, or climate-related financial losses. This study focuses primarily on statistical significance and interaction mechanisms. Future work should quantify the economic magnitude of ESG impacts —such as effect sizes per standard deviation change and cost-benefit comparisons across ESG sub-pillars — to better guide policy design and corporate investment strategies.

The findings highlight the complex relationship between climate-related challenges, limited financial resources, and ESG engagement. They point to the growing importance of adopting digital solutions and leveraging sustainable finance tools to overcome financial barriers and support long-term environmental and governance efforts. The study underscores that a company's ability to remain financially stable plays a key role in navigating climate risks and implementing meaningful ESG initiatives. For sustainable progress to be achieved, both business leaders and policymakers must foster conditions that encourage cohesive ESG strategies and support sustainable growth models, benefiting not only individual firms but the broader community as well.

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The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AI Statement

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to improve language clarity and ensure consistency in academic tone. After using this tool, the author(s) thoroughly reviewed and revised the content to ensure accuracy and originality. The authors take full responsibility for the content of the publication.

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