

Twin Transition: Do 5G Applications Really Improve Corporate Environmental, Social, and Governance (ESG) Performance?

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Abstract

Twin Transition denotes the dual transformation toward digitalization and sustainability. The concept is promising but lacks empirical evidence whether digital infrastructure really improves environmental conditions or on the contrary. This study adopts the difference-in-difference (DID) model to examine the impact of China's policy shock of 5G Pilot Program on enterprises' environmental, social, and governance (ESG) performance. The policy was carried out in batches across 40 scientifically selected cities, forming quasi-natural experiment. Using panel data covering 50,838 A-share listed firms from 2009 to 2024, we find adopting 5G improved the ESG performance of enterprises. Mechanism tests show two mediating paths: accelerated corporate digital transformation and promoted green technological innovation. Heterogeneity analysis showed stronger effect for non-state-owned enterprises, in high-tech industries, and in the eastern region of China. This study provides empirical evidence at firm level for the interaction mechanism between digitalization and sustainability, lending reference for informed strategy formulation and governance.

Keywords: *Twin Transition; ESG Performance; 5G; Digitalization; Green Innovation*

JEL Classification: G30, G38, L96, O33

1.Introduction

In an effort towards sustainable development, governments and firms increasingly turn to digital technologies. The idea of “twin transition” has been circulated in the World Economic Forum (Blüm, 2022), which denotes the simultaneous transformation toward digitalization and sustainability (Faggian et al., 2025; Trevisan et al., 2024; Tabares et al., 2025). Digital technologies are expected to raise resource efficiency, cut environmental externalities, and strengthen governance transparency, so that expected to support environmental, social, and governance (ESG) objectives (Li et al., 2024; Li & Zhu, 2024; Yu et al., 2025). Among the technologies, the fifth-generation mobile communication (5G) serves as a promising technology and potential future infrastructure. It allows industries to seamlessly connect, communicate, including deploy the Internet of Things (IoT) (Choi et al., 2022).

Despite these positive expectations, existing studies still debate the environmental impact of digitalization, especially massive digital infrastructure building. One stream of research suggests that digital infrastructure can speed up both digital development and environmental improvement. For example, digital technologies help firms use resources more efficiently, monitor environmental conditions in real time, and adopt cleaner production methods (Williams & Bergman, 2023). Empirical evidence supports this optimistic perspective. Gao et al. (2026) show that digital infrastructure reduces carbon emission intensity among Chinese listed industrial firms by enhancing green innovation and promoting digital coordination within industries. Similarly, Li and Fu (2026)

show that advances in information and communication technology substantially enhance environmental sustainability within China's resource-based cities. Tian et al. (2025) further find that the expansion of digital infrastructure facilitates urban green transformation, although the impact follows a U-shaped nonlinear pattern. At the policy level, Li and Yang (2025) find that the Broadband China initiative substantially enhanced city air quality.

Another stream of research raises concerns that digital infrastructure may instead hinder environmental sustainability. Economist William Stanley Jevons (1865) put forward Jevons Paradox that when technological progress improves efficiency, resource consumption does not decrease but increases. Scholars argue that the environmental benefits generated by digital technologies may be offset by the substantial energy consumption associated with their construction and operation. For example, Ferreboeuf et al. (2019) found that the energy consumption of 5G base stations is three to four times that of 4G base stations. If deployed on a large scale, this energy consumption gap will increase the environmental pressure. In addition, after the improvement of technical efficiency, enterprises might expand the scale of production, resulting in an increase in total energy consumption and carbon dioxide emissions (Lange et al., 2020). The above different views show that digital infrastructure does not always improve the environment. Its net effect depends on the institutional background and application scenario.

Although extant literature has discussed the economic and environmental consequences of digital infrastructure, several important gaps remain. First, most studies focus on traditional digital infrastructure, such as broadband networks or Internet penetration rates (Jin et al., 2023; Wang et al., 2022). Relatively few studies have examined next-generation communication technologies, especially 5G, and even fewer studies identify the causal effects of 5G-related policies. Second, emerging literature on 5G mainly examines its impact at the urban level, or focuses on individual behavior (Guo et al., 2022; Wang et al., 2026). Research at the firm-level is still scarce, and most of it focuses on corporate value (Jeon et al., 2022) or operational efficiency (Jiang & Xu, 2024). It is worth noting that ESG is a key indicator to measure the effectiveness of twin transition strategies, but there is not enough research on the impact of 5G infrastructure on the ESG performance of enterprises.

To address these gaps, we take China as the empirical background to examine the impact of 5G technology adoption on the ESG performance of enterprises. China provides a unique setting to examine the twin transition for two reasons. First, China has the largest independent 5G network and is vigorously promoting national strategies for both digital growth and green development (Jiang & Murmann, 2022). This combination of policies creates a background setting suitable for observing how digital infrastructure interacts with sustainability. Second, China's Ministry of Industry and Information Technology (MIIT) issued 5G commercial licenses to four telecom companies and started the 5G Technology Pilot Program across 40 cities in 2019 (China Briefing, 2019). From a top-down design, the 40 pilot cities were carefully selected to represent all levels of development and other characteristics. The program expanded gradually across regions, forming a quasi-natural experiment that allows analysis of 5G-enabled digital infrastructure on firm outcomes at the aggregate level. This present study uses the 2019 rollout of the first group of 5G pilot cities as an external policy shock and links it to panel data on A-share listed firms, applying a Difference-in-Difference (DID) model to measure how the 5G pilot Program influences firms' ESG outcomes.

We find that the implementation of the 5G Technology Pilot Program substantially enhances corporate ESG performance. Mechanism analyses show that this effect occurs via two main pathways: accelerating corporate digital transformation and promoting green technological innovation. Results from heterogeneity tests indicate that the improvement in ESG performance is greater for non-state-

owned firms, companies in eastern regions, and firms in high-technology industries.

This paper makes three main contributions to existing research. First, it separates the specific effect of 5G technology from that of general digital infrastructure investment. Unlike previous studies mainly examined internet penetration or broadband expansion (Jin et al., 2023; Luo et al., 2022), we exploit the 5G Technology Pilot Program to isolate the causal effect of next-generation digital infrastructure, helping clarify debates about 5G's environmental effects (Lange et al., 2020; Wang et al., 2024). Second, this study also adds to the twin transition literature by providing micro-level empirical evidence based on corporate ESG outcomes, bridging the gap between digital capability development and non-financial corporate performance. Third, it shows that digital transformation and green technology innovation act as mediating channels. These findings indicate that 5G investment can create social benefits at the firm level and support the rationale for public investment in new digital infrastructure.

2. Literature Review

2.1 Twin transition: Digitalization and Sustainability

Twin transition refers to the dual Journal of Business Research process in which firms pursue environmental sustainability alongside digital transformation (Brueck et al., 2025). Governments increasingly consider digital technologies important for supporting sustainable economic systems. Technologies such as artificial intelligence (AI), cloud computing, and the Internet of Things (IoT) enable enterprises to collect and analyze a large amount of data. This helps enterprises manage resources more effectively and adopt strategies to reduce environmental impact (Lin et al., 2025).

Existing research suggested multiple ways for digitalization to promote sustainable development. First of all, digital technology enables enterprises to continuously monitor and adjust the production process, thus improving the efficiency of resource utilization (Wang et al., 2024). Second, digital platforms can support circular economy practices, such as tracking the whole life cycle of products, implementing predictive maintenance, and reducing waste generation (Rusch et al., 2023). Third, digital systems can also improve the level of transparency and governance, making it easier for enterprises to monitor their environmental performance and ensure compliance (Zheng et al., 2025).

However, the impact of digitalization on sustainability remains unclear empirically. Some studies noted rebound effects, where efficiency gains lead to higher overall consumption (Qian et al., 2025). In addition, the operation of the digital economy also requires a large amount of energy and material resources in itself (Wang et al., 2023), which may increase its environmental footprint. The net effect of digitalization on sustainability at the firm-level is still an open question for empirical research to discover.

2.2 Digital Infrastructure and Corporate ESG Performance

As a critical metric, corporate ESG performance measures the practical performance of enterprises in sustainable development and shows their ability to create lasting value (Erzurumlu et al., 2025). ESG indicators cover environmental, social, and governance results, such as carbon emissions, labor practices, stakeholder engagement, and corporate transparency (Zhao et al., 2026).

Recent studies explored the impact of digital technology on ESG performance. Digital tools can improve the environmental performance of enterprises, including data-driven energy management, intelligent manufacturing systems, and optimized logistics networks (Chinnathai & Alkan, 2023; Hafeez et al., 2025). For example, digital monitoring technologies allow enterprises to accurately track emissions and resource consumption. This helps enterprises comply with environmental regulations and fulfill their obligations to report on social responsibility (Lodhia et al., 2025).

Digital tools have also had an impact on society and governance. Information systems can improve transparency, strengthen internal control mechanisms, and promote communication with stakeholders (Chen et al., 2025). Digital platforms can also improve the safety and well-being of employees through remote monitoring, automated operation, and intelligent management of the workplace (Nevi et al., 2025).

Despite the above theoretical association, there is still a lack of empirical evidence on the link between digital infrastructure and ESG. Most existing studies focus on digital transformation or IT investment at the firm-level, rather than the broader impact of public digital infrastructure (Jin et al., 2023; Wang et al., 2022). How infrastructure-level digitalization shapes the sustainable development performance of enterprises is still not fully understood.

2.3 5G-enabled Industrial Internet and Corporate Transformation

5G technology represents an advance in digital infrastructure. This technology provides higher data transmission speed, lower delay, and can connect a large number of devices at the same time. These features are just suitable for industrial application scenarios with high requirements for data flow rate and sensor network scale.

When 5G technology is combined with industrial systems, the concept of the Industrial Internet has emerged. The Industrial Internet closely connects all kinds of machinery and equipment, production lines, and management platforms. Enterprises can use these network architectures to deploy and operate advanced technologies, such as predictive maintenance, automated quality inspection, and digital twins (Afrin et al., 2025), improving efficiency and lower resource use.

Furthermore, the deployment of 5G infrastructure may accelerate corporate digital transformation by lowering technological barriers and enabling firms to adopt advanced digital applications (Jiang & Xu, 2024). As firms increasingly integrate digital technologies into their production and management systems, they may become better positioned to pursue sustainability-oriented innovations.

However, the sustainability implications of 5G infrastructure remain uncertain. The construction and operation of 5G networks require substantial investment in communication equipment and energy-intensive data processing facilities. Consequently, it is unclear whether the environmental benefits of digital optimization outweigh the environmental costs of network deployment.

3. Hypothesis Development

3.1. 5G Infrastructure and Corporate ESG Performance

As a key driver of next-generation digital infrastructure, the 5G technology improves communication network conditions and provides essential technological support for firms' digital

applications (Jiang & Xu, 2024). From the perspective of General Technology Theory (Bresnahan, 2010), the core economic value of 5G lies not in its own deployment, but in driving downstream applications across various industries. Although base station construction and operation do consume energy and raise concerns about Jevons Paradox and digital carbon footprint, the theory suggests that the systemic efficiency gains generated by digital empowerment across sectors far outweigh the direct energy consumption of digital infrastructure itself (Kunkel & Matthes, 2020).

The enhanced connectivity enabled by 5G networks improves firms' capabilities in information acquisition, data processing, and operational coordination across production, management, and information disclosure activities (Taboada & Shee, 2021). These changes help to narrow the information divide, improve the efficiency of internal governance, and enhance corporate transparency.

At the same time, governments often link support for 5G technology with relevant plans to develop the digital economy and encourage green growth. Such institutional frameworks encourage enterprises to integrate sustainable development goals into their strategic planning and daily operations. Through these channels, the 5G Technology Pilot Program can promote enterprises to achieve collaborative improvement in environmental, social, and governance practices. Based on the above logic, this study put forward the first hypothesis:

H1: The implementation of the 5G Pilot Policy enhances firms' ESG performance.

3.2. Digital Transformation as a Mediating Mechanism

5G networks have technical characteristics of high-speed data transmission, low delay, and massive device connection ability (Dolgui & Ivanov, 2022). These features provide the basic conditions for enterprises to accelerate digital transformation. According to the Resource-Based View (RBV), a firm's sustained competitive advantage stems from its valuable, rare, and inimitable internal resources and capabilities (Barney, 2001). However, cultivating digital capabilities typically entails substantial upfront capital investments and technical barriers. The 5G Technology Pilot Program provides vital public network infrastructure, dramatically reducing the deployment costs of enterprise software, data analytics platforms, and industrial IoT. The 5G technology Pilot Program reduces the additional cost of enterprises using digital tools and encourages enterprises to increase investment in digital systems in production, supply chain, environmental monitoring, and corporate governance, thereby fostering critical internal digital capabilities.

With the deepening of the digital integration of enterprises, firms effectively translate these newly accumulated digital assets into dynamic governance routines. Under the RBV framework, internal digital capabilities allow the firm to integrate internal information more effectively and track key operational indicators such as energy consumption, pollutant emissions, and operational risks in real time (Rai et al., 2006). These capabilities help enterprises carry out environmental management more efficiently and meet relevant regulatory requirements. In addition, digital transformation not only improves information transparency, but also strengthens the communication mechanism between enterprises and various stakeholders, such as employees, customers, and regulators, making corporate non-financial data verifiable and objective. The above improvements help to build a more stable governance structure and improve the performance of corporate social responsibility (Che et al., 2023). Therefore, digital transformation may be a key transmission path for the 5G Pilot Policy to promote the improvement of corporate ESG performance. Based on this:

H2: The 5G pilot policy improves firms' ESG performance by promoting corporate digital transformation.

3.3. Green Technology Innovation as a Mediating Mechanism

The improvement of digital infrastructure has also created a more efficient information environment for technological innovation (Ciarli et al., 2021). According to the Porter Hypothesis, well-designed environmental and technological inducements stimulate enterprises to engage in substantive technological innovation, generating “innovation offsets” that partially or fully offset compliance costs (Porter & Linde, 1995). By promoting the rapid transmission of data and the smooth exchange of knowledge, the 5G network effectively reduces the coordination cost and uncertainty in the process of research and development activities. High-speed connectivity facilitates knowledge recombination and shortens the R&D cycle for green technologies by enabling complex digital twin simulations and accelerating external technological spillover absorption. As a result, companies operating in regions possessing advanced digital infrastructure tend to increase their investments in green technological innovation.

Green innovation allows firms to create cleaner production technologies, reduce resource consumption, and improve environmental performance (Lv et al., 2021). thereby realizing innovation offsets that optimize resource utilization and lower environmental penalties. Meanwhile, firms pursuing green technological initiatives can enhance their corporate reputation and show greater commitment to social responsibility, generating positive spillover effects through social and governance aspects of ESG performance (Zhou et al., 2026). Therefore, the 5G Technology Pilot Program may also influence ESG outcomes through the promotion of green technological innovation. Therefore:

H3: The 5G pilot policy improves firms' ESG performance by promoting green technological innovation.

Based on the above theoretical analysis, Figure 1 illustrates the overarching conceptual framework of this study. It delineates the direct impact of the 5G Technology Pilot Program on corporate ESG performance (H1), along with the two mediating pathways operating through corporate digital transformation (H2) and green technology innovation (H3).

[Insert Figure 1 about here.]

4. Research Design

4.1. Data Sources and Sample Selection

This research uses panel data of Chinese publicly listed A-share firms between 2009 and 2024 to investigate the impact of the 5G Pilot Program on corporate ESG performance. Policymakers of the 5G Technology Pilot Program selected 40 cities to represent diverse industrial, geographical, and societal backgrounds against which 5G adoption would unfold across China. As publicly reported by various sources (China Briefing, 2019), these cities are distributed across all regions, spanning eastern to western provinces, and exhibit substantial heterogeneity in socioeconomic development and levels of technology adoption. Table 1 shows the differences across cities in GDP, population size, and total mobile phone account numbers.

Enterprises located in these pilot cities form the treatment group. The measurement of ESG of enterprises is based on the Huazheng ESG Database, which is often used in relevant research on listed companies in China (Fang & Hu, 2023; Zhong et al., 2025). Other firm-level variables are taken from the CSMAR database, consistent with previous studies (Gong et al., 2026; Xia et al., 2026).

We processed the original data as follows: (1) eliminate abnormal samples such as ST, * ST, and PT; (2) eliminate samples containing only a single observation value; (3) truncate the continuous variables at the level of 1%. After the above steps, the data set contains 50,838 listed companies every year. Due to missing values in some variables, the sample size in the empirical analysis may be slightly different.

[Insert Table 1 about here.]

4.2. Variable Definitions

4.2.1. Dependent Variable

ESG performance (ESG) is measured using Huazheng ESG Database, which is commonly used to measure the ESG performance of Chinese enterprises. Referring to Fang and Hu (2023) and Zhong et al. (2025), we convert the alphabet rating (C to AAA) into numbers from 1 to 9. The larger the number, the better the ESG performance.

4.2.2. Key Explanatory Variable

The core explanatory variable is the interaction term ($Treat*Post$). This interactive item combines the city virtual variable and the time virtual variable. Its calculation method is to multiply the virtual variable of the pilot city ($Treat$) by the time virtual variable ($Post$). If a city is a 5G pilot city, the value of $Treat$ is 1, otherwise it is 0. $Post$ is 0 before the implementation of the policy and 1 after the implementation. The coefficient of $Treat*Post$ measures ESG performance.

4.2.3. Mediating Variables

Digital transformation (DT) is assessed through text analysis, using the keywords identified by Wu et al. (2021). The DT index is calculated by taking the natural logarithm of one plus the total frequency of these keywords identified in each report.

Green technology innovation (GTI) is gauged using the citation count of a firm's green invention patents. To construct this variable, we take the natural logarithm of one plus the total number of patent citations, which reflects the firm's output and influence in green technology innovation.

4.2.4. Control Variables

Following Ouyang et al. (2025) and Yu et al. (2025), we include control variables to account for factors that could affect corporate ESG performance. Definitions and descriptive statistics of these variables are presented in Table 2 and 3.

[Insert Table 2 about here.]

[Insert Table 3 about here.]

4.3. Model Specification

To investigate the impact of the 5G Technology Pilot Program on corporate ESG performance, we estimate the following model:

$$ESG_{i,t} = \alpha_0 + \alpha_1 Treat * Post_{i,t} + \alpha_2 Control_{i,t} + \sigma_j + \lambda_t + \varepsilon_{i,t} \quad (1)$$

Here, $ESG_{i,t}$ represents ESG performance of firm i in year t . The interaction term $Treat * Post_{i,t}$ captures the effect of 5G Technology Pilot Program. $Control_{i,t}$ is a vector of control variables, while σ_j and λ_t denote firm and year fixed effects, respectively. $\varepsilon_{i,t}$ is the idiosyncratic error term. All regressions are estimated with robust standard errors.

To examine the mechanisms through which the 5G Technology Pilot Program influences ESG outcomes, we specify the following mediation models:

$$M_{i,t} = \alpha_0 + \alpha_1 Treat * Post_{i,t} + \alpha_2 Control_{i,t} + \sigma_j + \lambda_t + \varepsilon_{i,t} \quad (2)$$

$$ESG_{i,t} = \alpha_0 + \alpha_1 M_{i,t} + \alpha_2 Treat * Post_{i,t} + \alpha_3 Control_{j,i,t} + \sigma_j + \lambda_t + \varepsilon_{i,t} \quad (3)$$

Where $M_{i,t}$ denotes the mediating variables— DT and GTI . Definitions of other variables remain consistent with Equation (1).

5. Empirical Results

5.1. Benchmark Results

Table 4 presents the results of the benchmark regressions. To test the robustness of these findings, we adopt a stepwise regression approach. Column (1) only contains the core explanatory variables. In column (2), we have added control variables at the enterprise level. Column (3) further controls the fixed effect of enterprises and years. In the three models, the coefficients of $Treat * Post$ are all positive and have statistical reliability at the level of 1% or 5%. This shows that the 5G Pilot Policy helps to improve corporate ESG performance.

In column (3), the factors of enterprise, time, and individual characteristics are controlled at the same time. The results show that compared with enterprises in non-pilot cities, the 5G Pilot Policy has improved the ESG rating of enterprises in pilot cities by .107 points. This result strongly proves that 5G, as a new digital infrastructure, can effectively improve the ESG performance of enterprises and effectively promote the “Twin Transition” at the micro level. Regarding the control variables, the coefficients of *Enterprise Size*, *Indep*, and *Top1* indicators are all positive and significant. This means that larger enterprises with better corporate governance structures can usually achieve higher ESG performance. This finding is consistent with the research conclusions of (Broadstock et al., 2021). The results of the benchmark regression strongly support hypothesis 1.

[Insert Table 4 about here.]

5.2. Parallel Trend Test

The validity of the difference-in-differences (DID) model relies on the parallel trend assumption, which requires that before the implementation of the 5G Technology Pilot Program, the ESG performance of firms in both the treatment and control groups followed similar trajectories without systematic divergence. Building on this, this study draws on the event study approach (Miller, 2023), incorporates time dummy variables into the baseline regression, and establishes the following dynamic effect specification:

$$ESG_{i,t} = \alpha_0 + \sum_{k=-5, k \neq -1}^5 \alpha_k Treat * Post_{i,t}^k + \alpha_1 Control_{i,t} + \sigma_j + \lambda_t + \varepsilon_{i,t} \quad (4)$$

Where, $Treat * Post_{i,t}^k$ stands for a series of dummy variables. If the city where the firm i is registered is in the k year of the 5G Technology Pilot implementation in year t , $Treat * Post_{i,t}^k$ is set to 1; otherwise, it is 0. In this paper, we omit the year immediately preceding the policy rollout ($k = -1$), which serves as our baseline period. Consequently, the coefficient α_k captures the net difference in ESG outcomes between the treated and control firms relative to this reference year.

As depicted by the dynamic effects plotted in Figure 3, the estimated coefficients for all pre-treatment periods (from T-5 to T-2) hover near zero, with their 95% confidence intervals crossing the zero axis. This pattern indicates the absence of significant pre-existing differences in ESG performance between the two groups prior to the 5G pilot introduction, thereby strictly satisfying the parallel trend prerequisite. From the standpoint of the dynamic impact following the policy's implementation, the estimated coefficients of year t and year $t+1$ have not shown statistical significance, but from year T+2, the coefficients have significantly jumped to positive, and the confidence interval has completely deviated from the zero line, and remained significant in subsequent years (T+3 to T+5). These findings robustly validate that the 5G infrastructure initiative drives corporate ESG performance, while simultaneously demonstrating a policy transmission lag of approximately two years.

[Insert Figure 3 about here.]

5.3. Robustness Tests

5.3.1. Placebo Test

To further exclude the potential that our baseline findings are influenced by unobservable factors or random chance, we execute a placebo test by randomly assigning the 5G pilot status. More specifically, we select at random the pseudo-treatment group, which consists of the same number of businesses as the actual treated group, and assign a random “pseudo-implementation year”. We repeat this random sampling and estimation process 500 times.

Figure 2 shows the distribution of coefficient estimates in 500 simulations. The placebo coefficient is concentrated near the zero point, and the value is between -.080 and .08. The actual benchmark estimate is .107, which is located on the right side of these values and falls outside the cumulative distribution range of placebo estimates. This result implies that the positive impact of the 5G Technology Pilot Program on corporate ESG performance is a strong causal effect rather than an arbitrary artifact.

[Insert Figure 2 about here.]

5.3.2. Excluding Confounding Policies

During the sample observation period spanning 2009 to 2024, Chinese authorities also issued a series of macro-level policies concerning urban governance and digital infrastructure. If 5G pilot cities happen to be cities with overlapping implementation of these policies, the ESG improvement effect estimated in the benchmark regression may be mixed with the dividends of other policies. In order to accurately separate the net effect of 5G Technology Pilot Program enabling ESG, this paper focuses on excluding two representative policies that are highly similar to 5G construction in terms of implementation time and policy orientation: the Smart City Pilot Policy and the Broadband China Strategy.

To absorb the possible policy spillover effects, we incorporate the time point interaction term (dummy variable) of the two policies into the model for benchmark regression. Table 5 reports the regression results excluding policy intervention at the same time frame. As reported in Table 5, column (1) separately controls the Smart City Pilot Policy in the model, column (2) separately controls the Broadband China Strategy, and column (3) simultaneously incorporates these two policies into the model for strict testing. The results show that after accounting for the effects of the aforementioned pilot policies over the same period, the coefficient on the core interaction term *Treat*Post* remains significantly positive at the 1% level, with estimated values of .086, .088, and .089, respectively. The results suggest that the impact of the 5G Technology Pilot Program on the ESG performance of firms is not merely driven by concurrent digital or urban governance policies, but instead reflects an independent and robust causal effect.

5.3.3. Entropy Balancing

The choice of 5G pilot cities is not completely random, and is usually closely related to the local digital base and economic level, which may result in selection bias. In order to further overcome this potential endogenous problem, this paper uses the entropy balance method for robustness testing (Hainmueller, 2012). Compared with the traditional propensity score matching (PSM), the entropy balance approach allocates continuous weights to the control group to achieve an accurate balance with the processing group on the statistical moment of the given covariate (set as the first-order moment in this paper, that is, the mean value), and effectively avoids sample loss in the matching process.

We take all the enterprise characteristics in the benchmark model as covariates for entropy balance weighting, and re-conduct two-way fixed effect regression. As reported in column (4) of Table 5, the estimated coefficient on the key interaction term *Treat*Post* is .1178 and remains significantly positive at the 1% level. This indicates that after rigorously aligning the observable characteristics of the treatment and control groups and effectively mitigating sample selection bias, the conclusion that 5G Technology Pilot Program enhances corporate ESG performance continues to hold with strong robustness.

5.3.4. Other Robustness Tests

To further rule out potential confounding factors, we conduct a battery of supplementary robustness checks. First, to account for unobserved time-varying shocks at both the industry and

regional levels, *Industry*Year* and *Province*Year* fixed effects are sequentially introduced, as reported in columns (5) and (6) of Table 5. Second, to alleviate potential reverse causality between firm characteristics and ESG performance, all control variables are lagged by one period, and the baseline model is re-estimated (column (7)). Finally, to address concerns regarding outliers and sample attrition, we exclude firms located in China's four direct-controlled municipalities (Column (8)). Additionally, in order to generate a pseudo-balanced panel (Column (9)), limit the sample to enterprises that have been observed for a minimum of six years continuously. Across all these strict parameters, at the 1% or 5% levels, the *Treat*Post* coefficients continue to be considerably positive, strongly reinforcing the validity of our baseline findings.

[Insert Table 5 about here.]

5.4 Mechanism Analysis

Based on the hypothesis development, the 5G Technology Pilot Program is expected not only to directly improve corporate ESG performance, but also to generate indirect effects by accelerating corporate digital transformation and fostering substantive green technological innovation. To empirically examine these mechanisms, we use a stepwise regression method in order to test Hypotheses 2 and 3.

5.4.1. Accelerating Digital Transformation (DT)

The results of testing the digital transformation mechanism are presented in columns (1) and (2) of Table 6. At the 5% significance level, the coefficient on *Treat*Post* is .060, indicating that the 5G Technology Pilot Program substantially accelerates firms' digital transformation. In column (2), when digital transformation is included as an explanatory variable, its coefficient is .025 and significant at the 1% level, while the *Treat*Post* coefficient remains economically meaningful. The above implies that a partly mediation role is played by digital transformation. Specifically, the digitalization empowered by 5G networks enables firms to more effectively integrate internal information resources and strengthen real-time monitoring of energy consumption and governance risks, thereby realizing a coordinated improvement in ESG performance. Thus, Hypothesis 2 is supported.

5.4.2. Fostering Green Technology Innovation (GTI)

Columns (3) and (4) of Table 6 examine the GTI mechanism. In column (3), the coefficient of *Treat*Post* on GTI is .063 and significant at the 1% level, demonstrating that the 5G Technology Pilot Program substantially stimulates firms' green innovation activities. In column (4), GTI has a positive effect on ESG performance, with a coefficient of .046 (1% significant), and the *Treat*Post* coefficient declines but remains significant after including GTI. Green technological innovation plays an intermediary role in it. After the introduction of 5G infrastructure, enterprises will develop green technologies that help reduce environmental pollution. These technologies have improved the public image and governance practice of enterprises, and the two have jointly improved the ESG performance. This supports Hypothesis 3.

[Insert Table 6 about here.]

5.5 Heterogeneity Analysis

5.5.1 Ownership Structure

The type of corporate ownership is the primary determinant of all aspects of resource acquisition and decision-making processes in China's particular institutional environment. Regarding responses to policy shocks, state-owned enterprises (SOEs) often behave differently from non-state-owned enterprises (Non-SOEs). Columns (3) and (4) of Table 7 examine whether the 5G Technology Pilot Program's effect on ESG performance varies between SOEs and Non-SOEs. The coefficient of *Treat*Post* for SOEs is -.025 and not statistically significant, indicating that the policy has had negligible impact on the ESG performance of state-owned firms. In contrast, for Non-SOEs, the *Treat*Post* coefficient is .146 and significant at the 1% level, showing that the 5G Technology Pilot Program substantially enhances ESG performance in this sector. Compared with SOEs, Non-SOEs are more market-oriented, with shorter decision-making chains, and can react faster to policy signals and market opportunities, which can easily integrate 5G technology into ESG procedures. In contrast, SOEs must consider several objectives when making decisions, such as additional mandated government indicators, and their response time is slower (Wang et al., 2022). Besides, Non-SOEs face increased market rivalry and are driven to improve ESG performance using 5G technology, which improves brand image and market valuation in terms of resource allocation and incentive mechanisms. Furthermore, Non-SOEs management incentives are directly tied to corporate success, and they are more ready to invest in ESG innovation for 5G. In contrast, SOEs' incentive mechanisms are very conservative, and resources may be redirected to Non-SOEs.

5.5.2 Regional Differences

The economic foundation, digital infrastructure, industrial structure, human resources, and policy support of China's many regions differ significantly. Because of its first-mover advantage, the eastern region has surpassed the central and western areas in terms of digital economy and green development (Zhao & Dong, 2025). As a result, utilizing region as a grouping variable reveals how the 5G Pilot Policy affects different places with diverse degrees of growth. Columns (3) and (4) of Table 7 show that the 5G program significantly improves ESG performance for firms in the eastern region, with a *Treat*Post* coefficient of .141, significant at the 1% level. In contrast, the 5G Technology Pilot Program does not appear to significantly affect ESG performance in non-eastern regions, as the *Treat*Post* coefficient for central and western regions is .007 and statistically insignificant. First, the eastern region has more complete digital infrastructures in terms of differences in infrastructure and resources, such as 5G base stations, as well as richer scientific and technological talents and capital reserves. These advantages enable local enterprises to quickly apply 5G technology to ESG practices such as environmental monitoring and low-carbon production, while the central and western regions have obvious shortcomings in this regard (Ouyang et al., 2025). Second, the eastern area gained a sizable number of high-tech and high-value-added enterprises due to the synergy between industrial structure and policy. These businesses themselves are more inclined to invest in ESG construction, and 5G technology's enabling influence is more likely to become apparent. The eastern region, which is the national strategy's pioneer, has created a positive synergy effect between 5G regulations and other policies concerning technical innovation and green development (Liu & Zhu, 2024).

5.5.3 Industry Technological Characteristics

The industry's digital foundation and ability to absorb new technologies will determine how

transformative 5G technology is. The high-tech and non-high-tech industries inevitably differ in terms of technological reserves, innovation drive, and emphasis on ESG. To demonstrate how 5G rules affect ESG performance across diverse technology-intensive enterprises, this section of the research grouping variable is the sector's technological features. Similarly, as indicated in Table 7's columns (5) and (6), the high-tech industry's *Treat*Post* coefficient is .168, achieving statistical significance at the 1% level. The *Treat*Post* coefficient in the high-tech industry is .078 and significant at the 10% level, indicating that the 5G Technology Pilot Program markedly improves ESG performance in high-tech firms, with the strongest effect observed among all industry groups. This demonstrates that the strategy benefits the non-high-tech sector as well, although the impact's intensity and relevance are far lower than those of the high-tech sector. First, the high-tech sector with a stronger digital foundation is better adapted to 5G technology, and has lower integration costs, while non-high-tech industries face more difficult technological transition thresholds. Relatively speaking, these high-tech companies may quickly apply 5G technology to ESG scenarios such as carbon emission tracking and energy management optimization (Yang et al., 2025). Second, high-tech companies in terms of innovation capability and motivation typically have higher R&D capabilities and an innovation culture, alongside a greater willingness and ability to experiment with innovative 5G and ESG integration models. Non-high-tech sectors, on the other hand, have a comparatively low level of innovation and resource input.

[Insert Table 7 about here.]

6. Conclusions and Implications

6.1 Conclusions

This study attempts to explore the net causal influence of 5G digital infrastructure on corporate ESG performance in the context of the twin transition toward digitalization and sustainability. Using a difference-in-differences (DID) model, it analyzes the effects of China's 5G Technology Pilot Program enacted in 2019 on corporate ESG performance. The findings indicate that by encouraging digital transformation and green technology innovation, the 5G Technology Pilot Program greatly improved the ESG performance, and the positive effects tend to be more noticeable in non-state-owned enterprises, companies in China's east, and high-tech industries. This study's findings are significant on three levels. First, it isolates the net causal effect of next-generation communication technology, distinguishing 5G from general digital infrastructure. By conducting a quasi-natural experiment with the 5G Technology Pilot Program, this study addresses the "digital paradox" regarding the energy footprint of 5G, confirming its definitive role as an enabler rather than a polluter in the green transition. Second, it advances the Twin Transition theory by providing micro-level evidence anchored in corporate ESG performance. Third, it decodes the "black box" of the empowerment mechanism by identifying a dual pathway. This study highlights the substantial positive social externalities of 5G investments, offering a solid theoretical foundation for government initiatives in "New Infrastructure".

6.2 Implications

This paper suggests several implications as follows. First, in terms of infrastructure investment, due to the large positive externalities it generates, the government should reconsider the performance evaluation system for new infrastructure. Policymakers should incorporate the effects of ESG governance into the cost-benefit analysis framework of new infrastructure construction, moving from an “economic account” to a “comprehensive account”, as well as replacing the short-term investment-driven narrative with long-term green resilience empowerment. Second, given the significant disparities in the effects of 5G-enabled ESG across enterprises, regions, and industries, future policy resources should be moderately allocated to the central and western regions, traditional industries, and small and medium-sized enterprises. This can be accomplished by creating special digital transformation guidance funds, 5G application trial-and-error tolerance mechanisms, and technology diffusion subsidies to increase the technological absorption capacity of weaker entities. Third, regarding institutional assessment, we advocate integrating digital metrics deeply into ESG evaluation frameworks. Because 5G empowers ESG performance through a “dual-engine” pathway, regulators should explicitly incorporate process indicators such as digitalization levels and green patent quality into ESG disclosure rules. Moreover, policymakers should support corporate digital infrastructure to enable a transition from passive compliance to proactive governance, driving a reinforcing cycle of technological innovation and sustainable value generation.

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Declaration of Competing Interest

We confirm that this manuscript is original, unpublished, and not under review elsewhere. All listed authors have read and approved it, and no qualified contributors are omitted. The author's order has been agreed upon by all. The Corresponding Author will serve as the sole contact with the Editorial Office, responsible for communication, revisions, and final proof approval.

Declaration of AI Use

During the preparation of this manuscript, the authors used generative artificial intelligence tools to assist with language editing and improving the clarity and readability of the text.

Figures and Tables

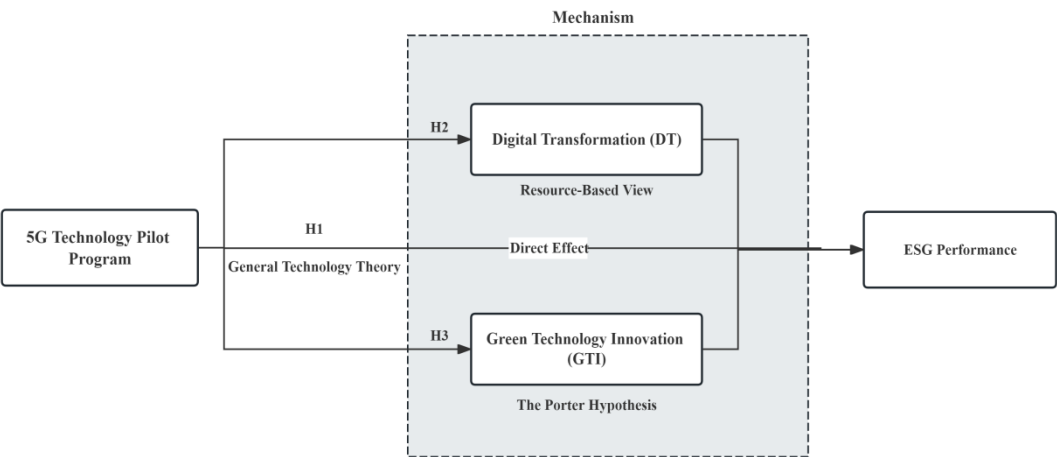


Figure 1. Conceptual Framework

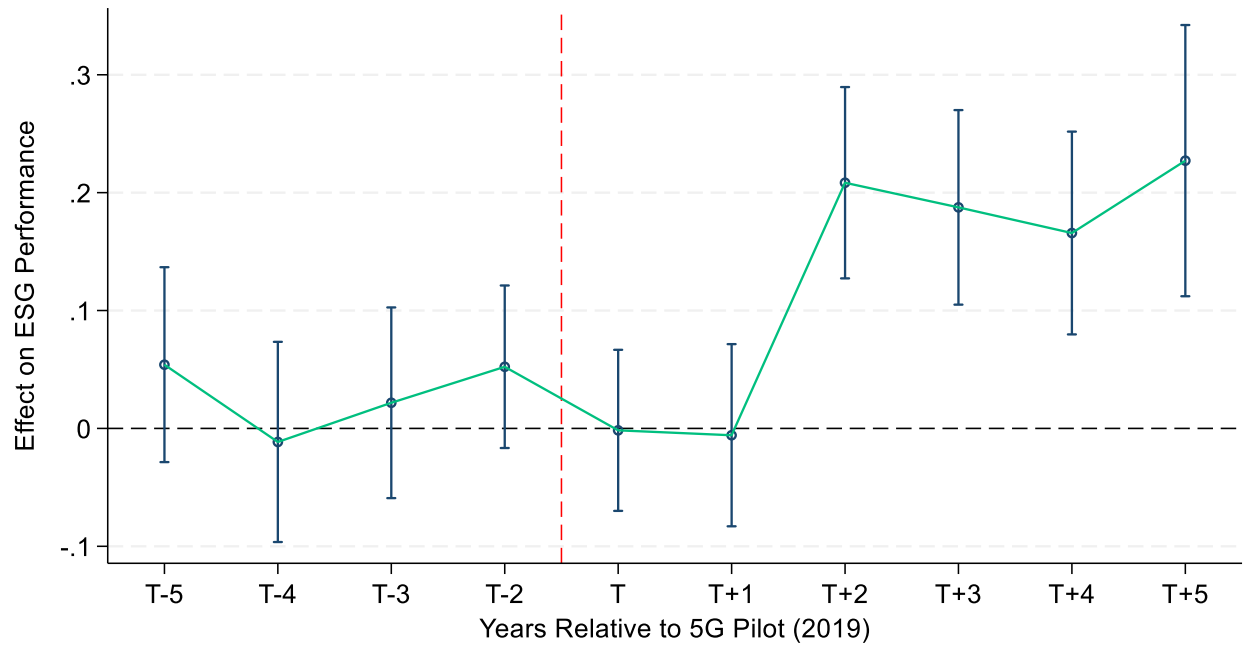


Figure 2. Parallel Trend Result

Note: T stands for 2019, the year when the policy was implemented. Pre 1 (2018) is excluded as the base period.

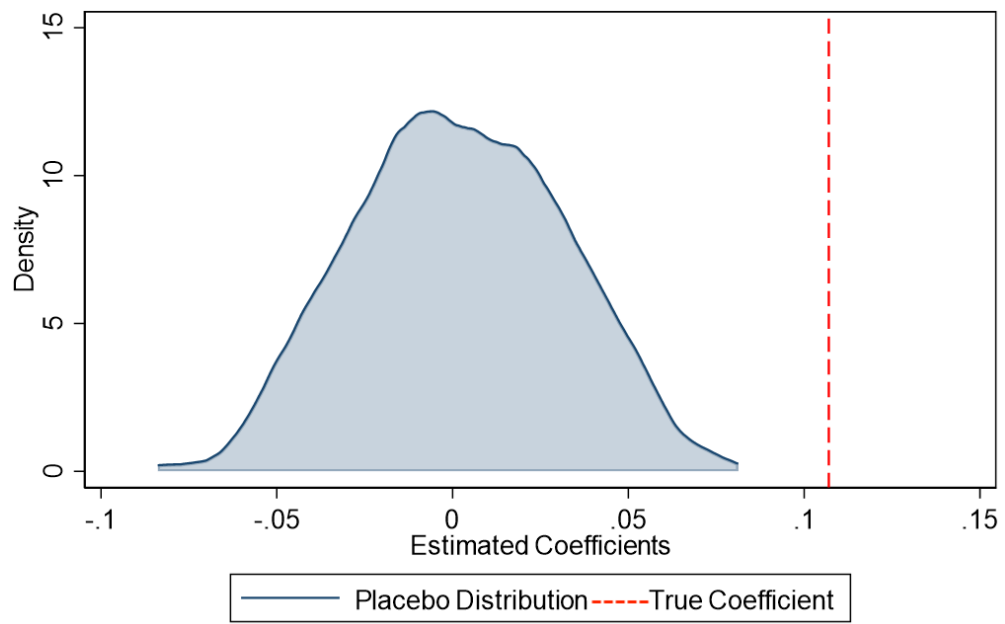


Figure 3. Placebo Test

Table 1. Lists of Cities to Receive 5G Technology Pilot Program in China

City	GDP (100 million CNY)	Registered Population (10,000 persons)	Mobile Phone Accounts (10,000 accounts)	City	GDP (100 million CNY)	Registered Population (10,000 persons)	Mobile Phone Accounts (10,000 accounts)
Shanghai	21,639	1,416	2,615	Hefei	4,662	619	578
Beijing	19,018	1,284	2,644	Changchun	4,067	757	743
Shenzhen	14,428	334	2,057	Shijiazhuang	4,034	983	815
Guangzhou	14,095	840	2,420	Wenzhou	3,886	791	879
Chongqing	12,412	3,294	2,111	Harbin	3,872	966	837
Suzhou	11,500	659	1,195	Kunming	3,322	543	714
Tianjin	10,422	1,014	1,104	Nanchang	3,155	501	477
Chengdu	8,951	1,246	1,763	Xiamen	3,147	200	428
Hangzhou	8,496	716	1,186	Nanning	2,514	674	605
Wuhan	8,466	840	1,123	Taiyuan	2,376	361	513
Nanjing	7,626	643	856	Guiyang	2,110	383	504
Qingdao	7,270	776	905	Hohhot	1,979	232	284
Ningbo	6,915	579	922	Urumqi	1,880	226	365
Changsha	6,351	670	820	Lanzhou	1,620	324	377
Zhengzhou	5,942	815	987	Yinchuan	1,106	167	241
Jinan	5,282	649	761	Zhangjiakou	1,032	460	267
Dalian	5,219	584	629	Haikou	932	158	258
Fuzhou	4,988	658	674	Xining	807	209	198
Xi'an	4,873	827	1,231	Lhasa	321	55	71
Shenyang	4,834	724	816				

Note: Gross Domestic Product, Registered Population, and Mobile Phone Accounts are obtained from the *China City Statistical Yearbook* (2000-2023), which represent the average values from 2000 to 2023. Data for the Xiong'an New Area are unavailable because it was established in 2017. The number of mobile phone accounts may exceed the total population, as individuals in China often maintain multiple accounts across different telecommunications providers, and organizations may register additional accounts for industrial equipment and operational purpose.

Table 2. Variable Definitions

Variable	Variable Name	Definition
<i>ESG</i>	Corporate ESG performance	Huazheng ESG ratings
<i>Treat*Post</i>	5G Technology Pilot Program	Interaction term between the city and time dummy variables
<i>Size</i>	Firm size	Logarithm of total assets
<i>ListAge</i>	Firm age	The natural logarithm of the number of years since the firm's listing.
<i>Lev</i>	Leverage ratio	Ratio of total liabilities to total assets
<i>ROA</i>	Profitability	Return on assets
<i>Top1</i>	Shareholding ratio of the largest shareholder	Proportion of the largest shareholder in the current year
<i>Tobin Q</i>	Market value	Tobin's Q ratio
<i>Indep</i>	Proportion of independent directors	Proportion of independent directors in the company during the year
<i>Dual</i>	CEO duality	A dummy variable indicating role duality between the chairman and the general manager. 1 indicates the two positions are held by the same individual and 0 otherwise.
<i>CashFlow</i>	Corporate cash flow	Ratio of net operating cash flow to total assets

Table 3. Descriptive Statistical Analysis

Variable	Obs	Mean	Std.	Min	Max
<i>ESG</i>	50,838	73.023	5.637	36.620	100
<i>Treat*Post</i>	50,838	.326	.469	0	1
<i>Size</i>	50,838	22.238	1.501	11.348	31.519
<i>ListAge</i>	50,838	2.059	.924	0	3.555
<i>Lev</i>	50,838	.444	1.102	-.195	178.346
<i>ROA</i>	50,838	.031	.591	-51.947	108.366
<i>Top1</i>	50,838	.335	.151	.003	.900
<i>TobinQ</i>	50,838	2.477	66.372	.609	1,481.310
<i>Indep</i>	50,838	.376	.055	0	.818
<i>Dual</i>	50,838	.300	.458	0	1
<i>CashFlow</i>	50,838	.044	.095	-1.216	2.222

Table 4. Baseline Regression Results

	(1) <i>ESG</i>	(2) <i>ESG</i>	(3) <i>ESG</i>
<i>Treat*Post</i>	.039** (.017)	.079*** (.016)	.107*** (.029)
<i>Size</i>		.258*** (.007)	.295*** (.015)
<i>ListAge</i>		-.289*** (.010)	-.264*** (.019)
<i>Lev</i>		-.049 (.043)	-.018 (.017)
<i>ROA</i>		.093*** (.016)	.007 (.009)
<i>Top1</i>		.131** (.064)	.314*** (.109)
<i>TobinQ</i>		.001** (.000)	.000** (.000)
<i>Indep</i>		1.027*** (.153)	1.090*** (.162)
<i>Dual</i>		-.023 (.017)	-.021 (.020)
<i>CashFlow</i>		.886*** (.088)	.028 (.062)
<i>Constant</i>	4.138*** (.012)	-1.493*** (.160)	-2.433*** (.345)
Observations	50,838	50,838	50,838
R-squared	.004	.137	.471
Year FE	NO	NO	YES
Firm FE	NO	NO	YES

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; robust standard errors are shown in parentheses.

Table 5. Robustness Tests

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>
<i>Treat*Post</i>	.086*** (.029)	.088*** (.029)	.089*** (.029)	.1178*** (.0203)	.1154*** (.0302)	.0870** (.0356)	.1008*** (.0205)	.0580*** (.0209)	.1057*** (.0188)
<i>Constant</i>	-.715** (.328)	-.404 (.349)	-.435 (.349)	-3.4152*** (.2644)	-2.5369*** (.3463)	-3.7424*** (.4746)	-1.8324*** (.2492)	-2.9695*** (.2614)	-2.4267*** (.2228)
Observations	40,951	34,710	34,710	50,838	50,766	36,850	44,221	40,712	44,694
R-squared	.502	.519	.519	.4842	.5180	.5129	.4868	.4703	.4598
Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
Smart City (Control)	YES	NO	YES	NO	NO	NO	NO	NO	NO
Broadband China (Control)	NO	YES	YES	NO	NO	NO	NO	NO	NO
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry*Year FE	NO	NO	NO	NO	YES	NO	NO	NO	NO
Province*Year FE	NO	NO	NO	NO	NO	YES	NO	NO	NO

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; robust standard errors are shown in parentheses.

Table 6. Mechanism Analysis

	(1)	(2)	(3)	(4)
	<i>DT</i>	<i>ESG</i>	<i>GTI</i>	<i>ESG</i>
<i>Treat*Post</i>	.060** (.026)	.105*** (.029)	.063*** (.015)	.104*** (.026)
<i>DT</i>		.025*** (.008)		
<i>GTI</i>				.046*** (.010)
<i>Size</i>	.226*** (.016)	.289*** (.016)	.093*** (.011)	.216*** (.014)
<i>ListAge</i>	.127*** (.018)	-.267*** (.019)	.183*** (.013)	-.285*** (.017)
<i>Lev</i>	.000 (.003)	-.018 (.017)	.010*** (.002)	-.018 (.014)
<i>ROA</i>	-.009 (.005)	.007 (.009)	-.006 (.006)	-.002 (.008)
<i>Top1</i>	-.354*** (.115)	.323*** (.109)	-.117 (.076)	.173* (.101)
<i>TobinQ</i>	.000*** (.000)	.000** (.000)	-.000 (.000)	.000** (.000)
<i>Indep</i>	-.356** (.139)	1.099*** (.162)	-.092 (.110)	1.143*** (.150)
<i>Dual</i>	.024 (.018)	-.021 (.020)	-.009 (.012)	-.022 (.019)
<i>CashFlow</i>	-.131** (.051)	.030 (.062)	.030 (.036)	-.025 (.061)
<i>Constant</i>	-3.593*** (.363)	-2.345*** (.348)	-1.909*** (.251)	-.593* (.309)
Observations	50,802	50,802	45,350	45,350
R-squared	.797	.471	.731	.500
Year FE	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; robust standard errors are shown in parentheses.

Table 7. Heterogeneity Analysis

	SOE	Non-SOE	East	Non-East	High-Tech	Non-High-Tech
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>	<i>ESG</i>
<i>Treat*Post</i>	-.025	.146***	.141***	.007	.168***	.078*
	(.049)	(.035)	(.034)	(.052)	(.036)	(.045)
<i>Size</i>	.310***	.332***	.323***	.274***	.322***	.277***
	(.026)	(.022)	(.021)	(.027)	(.021)	(.023)
<i>ListAge</i>	.177***	-.267***	-.278***	-.221***	-.379***	-.143***
	(.047)	(.023)	(.022)	(.038)	(.023)	(.032)
<i>Lev</i>	-.628***	-.010	-.151**	-.004	-.126	-.003
	(.126)	(.012)	(.063)	(.008)	(.077)	(.007)
<i>ROA</i>	-.067	.004	-.029*	.043	.011	.049*
	(.103)	(.009)	(.016)	(.028)	(.009)	(.027)
<i>Top1</i>	-.266	.458***	.462***	.056	.379**	.369**
	(.168)	(.146)	(.130)	(.197)	(.154)	(.153)
<i>TobinQ</i>	-.002	.000**	.018**	.000**	.001*	.005**
	(.006)	(.000)	(.007)	(.000)	(.001)	(.002)
<i>Indep</i>	1.161***	.888***	1.087***	1.085***	.861***	1.383***
	(.242)	(.211)	(.195)	(.278)	(.212)	(.237)
<i>Dual</i>	-.074*	-.004	-.034	.003	-.022	-.052
	(.040)	(.023)	(.023)	(.037)	(.025)	(.032)
<i>CashFlow</i>	-.017	-.006	-.005	.025	.012	-.058
	(.103)	(.076)	(.078)	(.108)	(.080)	(.102)
<i>Constant</i>	-3.335***	-3.252***	-3.024***	-2.082***	-2.675***	-2.513***
	(.582)	(.476)	(.463)	(.607)	(.471)	(.524)
Observations	16,815	33,948	36,186	14,646	30,132	20,643
R-squared	.492	.490	.471	.471	.470	.513
Year FE	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; robust standard errors are shown in parentheses.