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Digital transformation, green investment, and green transformation in manufacturing: empirical evidence from Chinese listed manufacturing firms

Yonghao Hong, Yun Chen*, Si Jian

Guangdong University of Science and Technology, Dongguan, China

*Corresponding Author. Email: chenyun@gdust.edu.cn

Abstract. Manufacturing firms are being pushed to reduce energy use and carbon emissions while continuing to improve productivity and product quality. Against this background, this paper examines whether digital transformation helps firms achieve greener modes of production and management. Using A-share manufacturing companies listed on the Shanghai and Shenzhen stock exchanges during 2012–2024, the study tests the effect of digital transformation on corporate green transformation and explores the role of green investment. The results show that firms with higher digital transformation scores tend to record better green transformation performance. This relationship remains statistically significant after firm-level controls, firm fixed effects, and year fixed effects are included. The mechanism evidence is conditional rather than universal. Green investment does not serve as a complete transmission channel in the full manufacturing sample, but it has partial explanatory power in heavily polluting industries. In these sectors, digital transformation is more likely to be converted into energy-saving equipment renewal, environmental facility construction, and cleaner production projects. Further heterogeneity tests show larger estimated effects in heavily polluting and high-tech manufacturing industries, although the group differences are not statistically significant. The findings provide firm-level evidence on the digital–green linkage in manufacturing and suggest that policies should promote targeted digital–green integration, especially in pollution-intensive sectors.

Keywords: digitalization, green transformation in manufacturing, green investment, heavily polluting industries

1. Introduction

Manufacturing remains central to China's real economy, industrial modernization, and global competitiveness. At the same time, many manufacturing activities still rely heavily on energy and material inputs and generate considerable carbon emissions. Sectors such as steel, chemicals, building materials, and equipment manufacturing have contributed substantially to economic growth, but they are also under increasing pressure to reduce energy use and carbon intensity. Against the background of China's "dual carbon" goals, green transformation in manufacturing is no longer a narrow issue of terminal pollution treatment. It has become a broader process of reshaping production methods, technological systems, and corporate environmental governance.

Prior studies have shown that the digital economy can support green transformation in manufacturing through industrial upgrading and technological progress [1]. At the firm level, digital transformation has also been found to improve carbon emission efficiency, green productivity, and carbon performance [2, 3]. Liu et al. [4] further argue that digital transformation contributes to manufacturing green development by enhancing innovation capability and production efficiency. Related evidence also links enterprise digital transformation to corporate carbon risk [5]. However, several issues still require further examination. First, more firm-level evidence is needed on whether digital transformation improves corporate green transformation outcomes. Second, it remains unclear whether digitalization is converted into concrete green investment behavior. Third, the green effect of digital transformation may differ across industries with different pollution pressures and technological foundations.

To address these issues, this study uses A-share listed manufacturing firms in Shanghai and Shenzhen from 2012 to 2024 as the research sample. It examines whether digital transformation promotes corporate green transformation, whether green investment serves as a transmission mechanism, and whether this relationship varies between heavily polluting and high-tech manufacturing industries. Specifically, this paper focuses on three questions: Does digital transformation improve the green transformation performance of manufacturing firms? Does green investment explain part of this relationship? Do industry pollution attributes and technological foundations shape the green enabling effect of digital transformation?

2. Theoretical foundations and research hypotheses

2.1. Digital transformation and green transformation in manufacturing

From the resource-based view [6], digital transformation can be regarded as a process in which firms convert data resources, digital technologies, operational knowledge, and managerial routines into organization-specific capabilities. For manufacturing firms, the green value of digital transformation does not come only from the adoption of digital tools, but from the extent to which these tools improve the visibility, coordination, and controllability of production and environmental management activities.

Digital technologies enable firms to monitor energy consumption, equipment operation, pollutant emissions, and resource utilization more accurately. With stronger data collection and information-processing capabilities, firms can identify energy waste, production inefficiencies, and environmental governance problems in a more timely manner. Digital transformation may therefore support green transformation by improving process optimization, cleaner production, green product development, and low-carbon management. Recent studies also suggest that digital transformation can improve green productivity, carbon emission efficiency, and corporate carbon performance in manufacturing firms [2, 3]. Accordingly, this study proposes the following hypothesis:

H1: Digital transformation has a positive effect on the green transformation of manufacturing firms.

2.2. Green investment as a transmission mechanism

Digital transformation may promote green transformation through firms' green investment decisions. On the one hand, digital technologies help firms identify environmental risks and evaluate the expected returns of green projects more effectively. On the other hand, digital transformation can improve internal resource allocation, enhance information transparency, and alleviate financing constraints, which may increase firms' willingness and ability to invest in environmental upgrading. Existing studies have shown that digital transformation can promote green innovation, improve carbon performance, and ease financing constraints [3, 4, 7]. Related evidence from heavily polluting listed firms also shows that enterprise digitalization can promote green technological innovation [8].

However, the transmission role of green investment may vary across industries. In industries with relatively low emission-reduction pressure, firms may improve green performance mainly through digital monitoring, process optimization, and management improvement. In heavily polluting industries, digital capabilities are more likely to be transformed into explicit green investment, such as energy-saving equipment renewal, pollution control facilities, cleaner production projects, and environmental management systems. These industries face stronger regulatory pressure and higher environmental compliance costs, so the green investment channel may be more evident. Accordingly, this study proposes the following hypothesis:

H2: Green investment plays a transmission role in the relationship between digital transformation and green transformation in manufacturing, and this mechanism is more pronounced in heavily polluting industries.

2.3. Heterogeneous effects of industry attributes

The green effect of digital transformation may differ across manufacturing industries because firms face different environmental pressures and possess different technological foundations. Heavily polluting industries usually have higher energy consumption and greater emission intensity. Under stricter environmental regulation and the "dual carbon" goals, these firms have stronger incentives to use digital technologies to monitor emissions, optimize equipment operation, reduce resource waste, and improve environmental governance. Therefore, digital transformation may generate a stronger green transformation effect in heavily polluting industries.

High-tech manufacturing industries may also benefit more from digital transformation. Compared with traditional manufacturing firms, high-tech firms usually have stronger technological absorptive capacity, better digital infrastructure, and higher knowledge intensity. These characteristics make it easier for them to embed digital technologies into green innovation, production optimization, and management upgrading [4]. Therefore, this study further examines whether the effect of digital transformation is stronger in high-tech manufacturing industries. Based on the above analysis, the following hypotheses are proposed:

H3a: The positive effect of digital transformation on green transformation is stronger in heavily polluting industries.

H3b: The positive effect of digital transformation on green transformation is stronger in high-tech manufacturing industries.

3. Research design

3.1. Sample selection and data sources

This study uses A-share listed manufacturing firms in Shanghai and Shenzhen from 2012 to 2024 as the research sample. The data are obtained by matching the green transformation index, digital transformation indicators, green investment data, and firm-level financial variables. After data cleaning and matching, the final sample includes 7,124 firm-year observations from 548 listed manufacturing firms. To reduce the influence of extreme values, continuous variables are winsorized. The empirical models include firm fixed effects and year fixed effects, and standard errors are clustered at the firm level.

3.2. Variable selection

The dependent variable is the Green Transformation Index (GTI). This variable is obtained from the CNRDS Green Transformation Thematic Database. It measures firms' green transformation performance from several dimensions, including energy conservation, emission reduction, green production, environmental governance, and green management. A higher GTI value indicates a higher level of corporate green transformation. This measurement is consistent with existing studies that examine green productivity, carbon performance, and green development in manufacturing firms [2, 3, 4].

The core explanatory variable is Digital Transformation (DT). This study measures DT by using the frequency of digital transformation-related keywords in firms' annual reports. The keyword dictionary includes "artificial intelligence", "blockchain", "cloud computing", "big data", "Internet of Things", "industrial Internet", and "intelligent manufacturing". Annual reports reflect firms' strategic attention to digitalization and their disclosed digital application practices. Keyword frequency has therefore been widely used to measure corporate digital transformation in related studies [3, 4, 9]. To reduce the skewness of the keyword frequency distribution, this study defines the logarithmic indicator in Equation (1):

$$DT_{it} = \ln\left(1 + DigitalWords_{it}\right) \tag{1}$$

where $DigitalWords_{it}$ denotes the total frequency of digital-related keywords appearing in the annual report of firm i in year t.

The mediating variable is green investment. This study mainly uses the natural logarithm of total green investment plus one to measure the green investment mechanism. In supplementary tests, green investment amount and green investment intensity are also used. Green investment mainly includes energy-saving equipment upgrading, environmental facility construction, cleaner production projects, and pollution control investment. These activities reflect the process through which firms convert digital capabilities into concrete environmental governance actions. Previous studies suggest that digital transformation can promote corporate green development by improving resource allocation efficiency, alleviating financing constraints, and facilitating green innovation [2, 7]. The logarithmic form of total green investment is defined in Equation (2):

$$\ln\_GI\_Total_{it} = \ln(1 + GI\_Total_{it}) \tag{2}$$

where GI_Total_{it} denotes the total green investment of firm i in year t. Green investment intensity is measured as the ratio of green investment to total assets.

The grouping variables include heavily polluting industries and high-tech manufacturing industries. HeavyPollution is constructed according to industry codes. Firms in C17, C19, C22, C25, C26, C27, C28, C29, C30, C31, and C32 are assigned a value of 1, while firms in other industries are assigned a value of 0. These industries usually face higher energy consumption, stronger emission pressure, and stricter environmental regulation, and are therefore key targets of green transformation under the "dual carbon" goals. (HighTechStrict) is also constructed based on industry codes. Firms in C27, C37, C39, and C40 are assigned a value of 1, while other firms are assigned a value of 0. High-tech manufacturing firms generally have stronger technological absorptive capacity and digital foundations, which may strengthen the role of digital transformation in production optimization, green innovation, and management upgrading [1, 4].

The control variables include firm size, leverage, profitability, and firm age. Size is measured by the natural logarithm of total assets at year-end. Lev is measured by the ratio of total liabilities to total assets. ROA is measured by the ratio of net profit to total assets. Age is measured by the natural logarithm of firm age plus one, as defined in Equation (3):

$$Age_{it} = \ln\left(1 + FirmAge_{it}\right) \tag{3}$$

where $FirmAge_{it}$ denotes the age of firm i in year t. These variables are included to control for differences in resource endowments, financial risk, profitability, life cycle stage, and organizational experience. They are commonly used in empirical studies on corporate digital transformation, green innovation, and green transformation [2, 3, 7].

3.3. Model specification

To test whether digital transformation contributes to the green transformation of manufacturing firms, this study first estimates the following baseline model (Equation (4)):

$$GTI_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{4}$$

In Equation (4), GTI_{it} represents the green transformation index of firm i in year t, and DT_{it} is the digital transformation indicator. $Controls_{it}$ refers to the vector of control variables. μ_i captures firm fixed effects, λ_t captures year fixed effects, and ε_{it} is the error term. Firm fixed effects are included to absorb unobserved firm characteristics that do not change over time, such as organizational culture, long-term strategic orientation, and basic production attributes. Year fixed effects are used to account for common shocks across firms, including macroeconomic fluctuations, policy adjustments, and changes in the external market environment. This two-way fixed effects setting is suitable for firm-level panel data and is also commonly adopted in related studies on digital transformation and green development [2, 3].

To further examine whether green investment serves as a mechanism linking digital transformation and green transformation, this study estimates the mediation models in Equations (5) and (6):

$$M_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{5}$$

$$GTI_{it} = \gamma_0 + \gamma_1 DT_{it} + \gamma_2 M_{it} + \gamma_3 Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{6}$$

Here, M_{it} denotes the green investment variable. Equation (5) examines whether digital transformation affects green investment, while Equation (6) tests whether green investment is associated with green transformation after controlling for digital transformation and other firm characteristics. If β_1 and γ_2 are both significantly positive, it suggests that green investment is an important channel through which digital transformation promotes green transformation. In essence, the mediation test identifies whether digital transformation first changes firms' environmental investment behavior and then improves their green transformation performance. This method follows the logic of classical mediation analysis [10] and has been widely used in research on digital transformation, green innovation, and carbon performance [3, 7]. Considering that the green investment channel may depend on industry characteristics, this study conducts the mechanism test for both the full sample and the heavily polluting industry subsample.

To analyze whether the effect of digital transformation varies across industry attributes, this study estimates the interaction model in Equation (7) and conducts subgroup regressions:

$$GTI_{it} = \delta_0 + \delta_1 DT_{it} + \delta_2 DT_{it} \times Group_i + \delta_3 Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{7}$$

In Equation (7), $Group_i$ represents the grouping variable, including heavily polluting industries and high-tech manufacturing industries. A significantly positive coefficient on the interaction term would indicate that the corresponding industry attribute strengthens the effect of digital transformation on green transformation. Subgroup regressions are then used to compare the coefficient size, direction, and significance level of DT across different types of firms. Since prior studies suggest that the green outcomes of digital transformation may be shaped by environmental pressure, technological capability, industry conditions, and firm-level resources [1, 2, 4], this study conducts heterogeneity analysis from two perspectives: pollution attributes and technological attributes.

4. Empirical results and analysis

4.1. Sample distribution

The empirical analysis is based on listed manufacturing firms observed from 2012 to 2024. After data matching and cleaning, the final panel contains 7,124 firm-year observations from 548 firms. The regressions control for both firm and year fixed effects, and the standard errors are clustered at the firm level.

The sample shows clear differences in industry attributes. Non-heavily polluting industries account for 3,328 observations from 256 firms, while heavily polluting industries account for 3,796 observations from 292 firms. In terms of technological attributes, non-high-tech manufacturing industries include 5,499 observations from 423 firms, and high-tech manufacturing industries include 1,625 observations from 125 firms. This distribution makes it possible to compare firms with different pollution pressures and technological foundations, and provides the empirical basis for the mechanism and heterogeneity tests.

4.2. Baseline regression results

The baseline results indicate a significant positive relationship between digital transformation and green transformation in manufacturing firms. After adding Size, Lev, ROA, Age, firm fixed effects, and year fixed effects, the coefficient of DT is 0.1063, significant at the 1% level. This means that firms with a higher degree of digital transformation tend to have a higher green transformation index. H1 is therefore supported.

This result is in line with Ni and Wu [2], who find that digital transformation improves green productivity in manufacturing, and Fang and Lin [3], who show that digital transformation contributes to better carbon performance. From an economic perspective, digital transformation should not be viewed only as a means of improving operational efficiency. It can also strengthen firms' green governance by improving energy-use monitoring, production scheduling, environmental information management, and coordination along the green supply chain.

4.3. Mediation test: the green investment mechanism

The full-sample results do not support a stable mediation path through green investment.

When the logarithm of total green investment is used as the mechanism variable (Figure 1), the coefficient of DT on green investment is 0.0473, but it is not statistically significant. The coefficient of green investment on GTI is 0.0123 and also fails to reach statistical significance. At the same time, the coefficient of DT on GTI remains 0.1063 and significant at the 1% level. These results suggest that, for the overall manufacturing sample, digital transformation promotes green transformation mainly through channels other than a broad increase in green investment.

The results are different for heavily polluting industries. In this subsample, the coefficient of DT on green investment is 0.1122 and significant at the 5% level. The coefficient of green investment on GTI is 0.0196 and significant at the 10% level. The direct coefficient of DT on GTI remains 0.1212 and significant at the 1% level. This implies that in industries with higher energy consumption, stronger emission pressure, and stricter environmental governance requirements, digital transformation is more likely to be converted into concrete green investment, such as energy-saving equipment renewal, environmental facility construction, and cleaner production projects. These investments then further contribute to firms' green transformation.

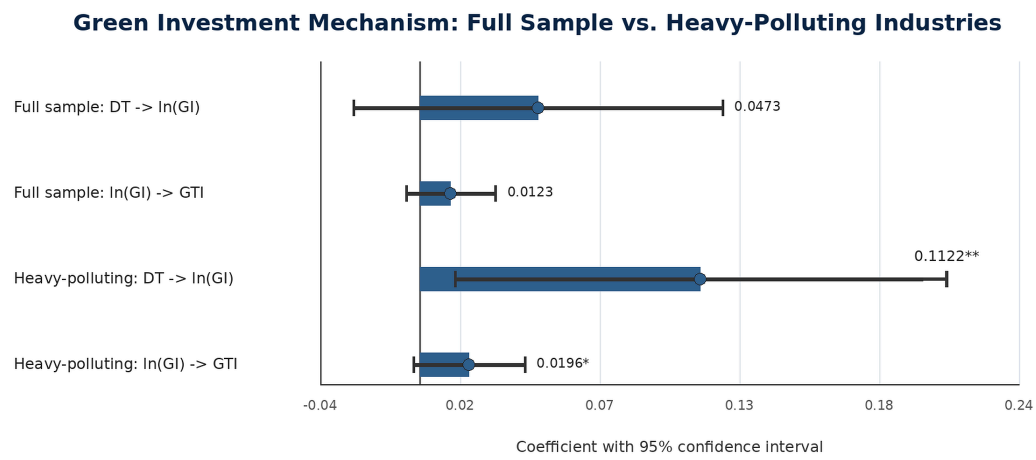

Figure 1. Green investment mechanism

Note: Error bars indicate 95% confidence intervals. ***, ** and * indicate statistical significance at the 1%, 5% and 10% levels respectively.

This finding is broadly consistent with Liu et al. [4], who emphasize the role of innovation capability and production efficiency in manufacturing green development. Overall, H2 is conditionally supported. The green investment mechanism is not evident in the full sample, but it has explanatory power in heavily polluting industries.

4.4. Heterogeneity analysis: heavily polluting industries and high-tech manufacturing industries

The heterogeneity results first show that digital transformation has a positive effect on green transformation in both heavily polluting and non-heavily polluting industries.

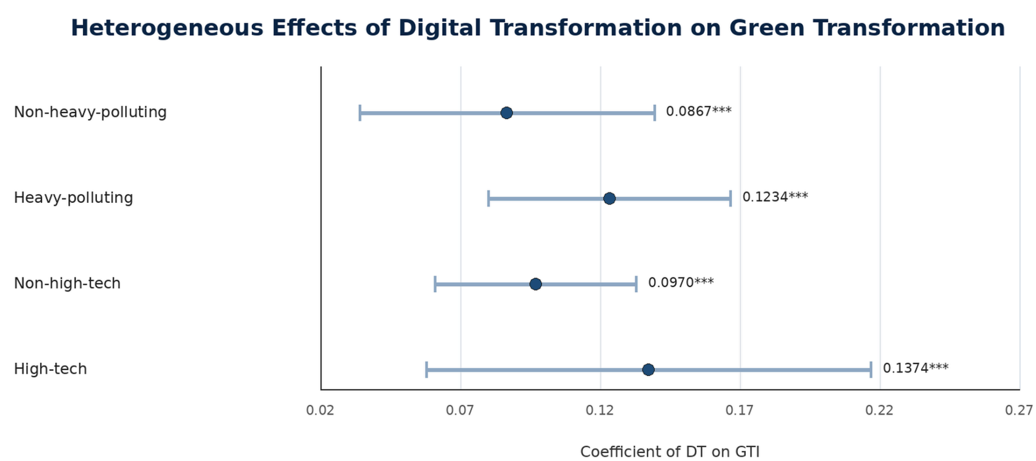

Figure 2. Heterogeneous effects of digital transformation on green transformation

Note: Error bars indicate 95% confidence intervals. ***, ** and * indicate statistical significance at the 1%, 5% and 10% levels respectively.

As shown in Figure 2, the coefficient of DT is 0.0867 for non-heavily polluting industries and 0.1234 for heavily polluting industries. Both coefficients are significant at the 1% level. The larger coefficient for heavily polluting industries indicates that digital transformation may generate greater marginal green benefits when firms face stronger pressure for energy conservation, emission reduction, and environmental compliance. However, the interaction term is only 0.0132 and is not statistically significant. Therefore, the evidence supports a stronger direction of effect in heavily polluting industries, but does not prove a statistically significant difference between the two groups.

The results for high-tech manufacturing industries show a similar pattern. The coefficient of DT is 0.0970 for non-high-tech manufacturing industries and 0.1374 for high-tech manufacturing industries, with both coefficients significant at the 1% level. The larger coefficient in high-tech manufacturing suggests that digital infrastructure, technological absorptive capacity, and knowledge intensity may strengthen the green effect of digital transformation. However, the interaction coefficient is 0.0063 and statistically insignificant. Thus, although the estimated effect is larger for high-tech manufacturing firms, the difference between high-tech and non-high-tech groups is not statistically confirmed.

Taken together, the heterogeneity analysis shows that the green enabling effect of digital transformation is not confined to a single type of manufacturing firm. It is significant across industries with different pollution characteristics and technological foundations. However, the stronger effects observed in heavily polluting and high-tech manufacturing industries are mainly directional rather than statistically significant. Therefore, H3a and H3b receive only directional support.

5. Discussion of results

Compared with studies that mainly use carbon performance, green innovation, or green productivity as outcome variables, this study adopts a comprehensive corporate green transformation index. The results suggest that the role of digital transformation is not limited to a single environmental outcome, but is reflected in firms' broader capabilities in green production, environmental governance, and low-carbon management. Manufacturing green transformation is difficult because energy use, emissions, equipment operation, and production processes are distributed across multiple stages. Traditional management methods often fail to identify key problems in a timely and accurate manner. By improving data collection, process monitoring, and intelligent decision-making, digital transformation helps shift green governance from ex post treatment to process-oriented management. This may explain why the positive effect of digital transformation remains stable in the baseline regressions.

The mechanism results provide a more nuanced explanation. In the full sample, green investment does not form a complete mediation path. This does not mean that digital transformation has no green governance mechanism. Rather, it suggests that the digital-green effect may operate more through process optimization, energy-use monitoring, production scheduling, equipment efficiency improvement, and environmental data management than through a general increase in explicit green investment. In addition, green investment data may be affected by firms' disclosure quality. Some firms may conduct energy-saving renovation, digital monitoring, or environmental management upgrading without separately reporting these expenditures as green investment. As a result, the measured green investment variable may not fully capture all green actions generated by digital transformation.

In heavily polluting industries, the green investment path receives partial empirical support. These firms face stronger environmental constraints, higher compliance costs, and more urgent equipment upgrading needs. Therefore, the identification and coordination capabilities generated by digital transformation are more likely to be converted into observable investment actions, such as energy-saving equipment renewal, environmental facility construction, and cleaner production projects. This finding indicates that digital transformation does not promote green transformation through a single universal channel. Instead, the mechanism depends on industry context: firms under stronger environmental pressure are more likely to transform digital capabilities into explicit green investment.

The heterogeneity results also require cautious interpretation. The DT coefficients are larger in heavily polluting industries and high-tech manufacturing industries, corresponding respectively to stronger emission-reduction pressure and stronger digital absorptive capacity. However, the interaction terms are not statistically significant. This means that the evidence supports only a directional difference, not a confirmed moderating effect. One possible explanation is that digital technologies have broad applicability across manufacturing industries. Energy management, equipment monitoring, intelligent scheduling, and environmental data governance can improve green transformation in both traditional and high-tech sectors. Industry attributes may influence the strength of the effect, but they do not yet constitute stable and statistically significant boundary conditions in this sample.

6. Conclusion and implication

Using a firm-level panel of listed manufacturing companies for 2012–2024, this paper examines whether digital transformation improves green transformation. The results show a positive and significant DT coefficient after controlling for firm characteristics, firm fixed effects, and year effects, indicating that digitalization is associated with higher green transformation performance. The mechanism evidence is more limited. Green investment does not operate as a complete transmission channel in the full sample, but it has partial explanatory power among heavily polluting firms, where environmental pressure makes digital capabilities more likely to be converted into equipment upgrading, pollution control, and cleaner production investment. Heterogeneity tests show larger DT coefficients in heavily polluting and high-tech manufacturing industries, yet the interaction terms are insignificant. Thus, pollution pressure and technological foundations may strengthen the digital–green linkage, but this moderating role remains directional rather than conclusive and requires further evidence.

Policymakers may consider promote the coordinated governance of digitalization and greening, and guide firms to integrate the industrial Internet, energy consumption monitoring, carbon management platforms, and green investment projects. For heavily polluting industries, support should be strengthened through green credit, technological upgrading subsidies, and zero-carbon factory initiatives. For high-tech manufacturing industries, digital–green synergy demonstrations should be further promoted. The limitations of this study lie in the fact that green investment data are affected by disclosure quality, and the mechanism tests remain relatively broad. Future research may further distinguish different types of green investment and identify the boundaries of the effect by incorporating environmental regulation, carbon trading, and green finance policies.

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