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The Impact of Green Transformation on Corporate Green Investment Efficiency: Evidence from China

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Abstract

As the global shift toward green and low-carbon development deepens, green investment has become a core component driving sustainable economic growth. This study addresses a key gap in the literature by systematically exploring how corporate green transformation affects green investment efficiency at the micro level. Using data from China's A-share listed corporations (2007–2022), we innovatively integrate the Global Malmquist-Luenberger (GML) index with an enhanced Richardson model incorporating environmental governance variables. Results demonstrate that green transformation significantly boosts investment efficiency, mainly by alleviating underinvestment. The study makes three key contributions: (1) identifying distinct regional and ownership-based heterogeneity effects; (2) uncovering uncertainty perception and labor employment as dual mediating mechanisms; and (3) verifying digital transformation's positive moderating role. These findings deliver targeted insights for optimizing green investment strategies during corporate transformation.

Keywords: green transformation; green investment efficiency; GML index; Richardson model; mediating mechanisms; digital transformation

1. Introduction

Against the backdrop of global climate change and increasingly stringent resource and environmental constraints, promoting the green and low-carbon transformation of economies and societies has become a global consensus. As the world's largest carbon emitter, China is actively responding to its “dual carbon” strategic goals by accelerating the development of a green, low-carbon, and circular economic system. In this process, corporations—as key implementers of green transformation—have attracted growing attention from academia, policymakers, and market participants regarding their green investment practices and the efficiency of such investments.

Green investment is a vital way for businesses to fulfill environmental responsibilities, seize future sustainable development opportunities, and enhance long-term competitiveness. According to a report released by the People's Bank of China, the outstanding balance of green loans in domestic and foreign currencies in China exceeded 30 trillion yuan by the end of 2023, representing a year-on-year increase of over 36%. These funds primarily flowed into projects with significant carbon reduction effects, reflecting robust green finance support for green transformation. However, despite the continuous growth in green investment scale, critical questions remain about the efficiency of fund allocation and the potential for over- or under-investment at the corporate level [1,2]. This discrepancy between scale and efficiency highlights a significant research gap and practical challenge.



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In recent years, Chinese corporations have intensified their green transformation efforts, with green technology upgrades, clean production modifications, and green supply chain management emerging as pivotal strategies for achieving high-quality development. During this process, corporations face cost pressures from technological innovation and equipment upgrades, as well as uncertainties such as unclear policy expectations and volatile market conditions [3,4]. These factors can significantly impact their green investment decisions and efficiency. Therefore, understanding how to enhance the efficiency of green investment allocation through effective green transformation has become a critical issue for corporations seeking to synergize economic and environmental performance.

Current research on green investment and transformation exhibits several limitations (see Table 1). Firstly, the literature predominantly focuses on the macro level, examining how national or industry policies drive green investment and its impact on sustainable economic development, while paying insufficient attention to specific investment efficiency and implementation processes at the corporate micro level [5,6]. Secondly, existing studies often emphasize the scale of green investment, with limited research on the effectiveness of fund utilization and the influence of different technologies and management models on investment efficiency, leaving efficiency-level analysis inadequate [7,8]. Thirdly, although green transformation encompasses low-carbon production, environmental technology adoption, and sustainable strategies, existing studies primarily explore its effects on financial performance, social responsibility, and brand image, with systematic exploration of how it enhances green investment efficiency remaining scarce [9,10]. Lastly, recent advancements in digital technologies have introduced new dimensions to both green transformation and investment efficiency. Emerging literature explores how Artificial Intelligence (AI), cloud computing, and blockchain can revolutionize energy markets and green finance [11–13]. However, how these digital tools interact with corporate green transformation to affect green investment efficiency remains underexplored.

Table 1. Summary of Literature Gaps.

Aspect	Focus	Gap
Analysis Level	Macro-level (national/industry policy impacts)	Lack of micro-level corporate analysis
Research Object	Scale of green investment	Limited analysis of investment efficiency
Transformation Link	Green transformation's impact on financial/ESG performance	Weak link to investment efficiency
Mechanisms	Technological and resource pathways	Neglect of behavioral (uncertainty) and structural (labor) mediators
Contextual Factors	Isolated examination of green or digital transition	Lack of integration
Methodology	Entropy, DEA, or standard investment models	Lack of integrated model for green efficiency

Given these substantial gaps, this study aims to address the following core research questions: (1) How does corporate green transformation affect green investment efficiency at the micro level? (2) What are the underlying mechanisms (e.g., uncertainty perception, labor employment) through which green transformation influences investment efficiency? (3) How does digital transformation moderate the relationship between green transformation and green investment efficiency? (4) How does this relationship vary across regions, ownership types, and industries?

The expected contributions of this study are threefold. Theoretically, by integrating green transformation theory with investment efficiency models, this study provides a micro-foundational framework linking corporate green strategies to investment outcomes. It also incorporates digital transformation as a moderating variable, bridging the literature on green and digital transitions. Methodologically, the combined use of the GML index [14] for green transformation measurement and an enhanced Richardson model [15] incorporating

environmental governance variables for investment efficiency offers a novel and robust empirical approach for assessing corporate green performance. Practically and policy-wise, the findings offer evidence-based insights for policymakers to design targeted green finance, labor, and digital policies, and for corporate managers to optimize green investment strategies during the complex process of dual (green and digital) transformation.

The remainder of the paper is structured as follows: Section 2 presents theoretical analysis and hypotheses; Section 3 describes the research design; Section 4 reports empirical results; Section 5 discusses the findings; and Section 6 concludes with implications and policy recommendations.

2. Theoretical Analysis and Research Hypotheses

This section establishes the theoretical foundation for the study, primarily drawing upon innovation diffusion theory, financial intermediation theory, and technological change theory, supplemented by the resource-based view and stakeholder theory. These theoretical lenses collectively articulate the intrinsic logic of how corporate green transformation influences green investment efficiency, explain the mediating mechanisms, and rationalize the moderating role of digital transformation. The selected theories provide direct theoretical support for constructing the research model, defining key variables, and formulating specific hypotheses.

2.1. *The Impact of Green Transformation on Corporate Green Investment Efficiency*

Innovation Diffusion Theory posits that the adoption of new technologies or practices within an organization is a process shaped by perceived benefits, compatibility, and complexity. Green transformation represents the diffusion and internalization of green technologies and sustainable management practices within a corporation. As this transformation deepens, the corporation enhances its capabilities in green technology application and process optimization, thereby improving the compatibility and efficiency of implementing green projects. This reduces the complexity and uncertainty associated with green investments, leading to more precise capital allocation and thus higher investment efficiency [10]. Therefore, from the perspective of innovation diffusion, green transformation is expected to elevate the overall efficiency of corporate green investment.

However, the impact on different types of investment inefficiencies may be asymmetric. Financial Intermediation Theory highlights the role of financial markets and institutions in mitigating information asymmetry and alleviating financing constraints. Green transformation improves a corporation's environmental performance and information transparency, sending positive signals to external investors and financial intermediaries. This helps reduce information asymmetry, lowers the risk premium demanded by creditors, eases financing constraints for green projects, and consequently alleviates underinvestment caused by capital shortages [16]. In contrast, overinvestment is often driven by agency conflicts or managerial expansion motives. While green transformation improves technical efficiency, it does not directly resolve principal-agent problems. Furthermore, under policy incentives, corporations might engage in excessive or symbolic green investments for strategic purposes, thereby weakening the constraining effect of green transformation on overinvestment. Based on the above theoretical analysis, this study proposes:

H1. *Green transformation can enhance corporate green investment efficiency.*

H1a. *Green transformation can significantly alleviate corporate underinvestment in green initiatives.*

H1b. *Green transformation has no significant impact on corporate overinvestment in green initiatives.*

2.2. Mechanisms Through Which Green Transformation Influences Corporate Green Investment Efficiency

2.2.1. The Mediating Role of Uncertainty Perception

Innovation Diffusion Theory and behavioral finance perspectives suggest that uncertainty surrounding new technologies and future policies is a key factor hindering their adoption and related investments. Corporations' perceptions of uncertainty regarding environmental regulations, green technology maturity, and market acceptance directly affect their willingness and timing to invest. Green transformation, by enabling corporations to master core green technologies and establish adaptive management systems, enhances their capacity to cope with external changes. This reduces management's perception of uncertainty regarding future business environments [3,4]. Lower perceived uncertainty encourages more proactive and timely green investments, thereby improving capital allocation efficiency. Based on this, Hypothesis H2 is proposed:

H2. *Green transformation enhances green investment efficiency by reducing corporate uncertainty perception.*

2.2.2. The Mediating Role of Labor Employment

Technological Change Theory emphasizes that technological progress alters production factors and input structures. Green transformation, as a form of directed technological change, involves adopting cleaner production technologies and automated equipment. This shifts the production process from reliance on traditional labor to dependence on technology and capital, reducing demand for routine labor. From a resource allocation perspective, this reduction in labor input and associated costs frees up internal resources that can be reallocated to more productive green innovation and environmental projects [17]. Optimizing the labor structure also reduces organizational inertia, allowing management to focus more on value-creating green investments, thereby improving investment efficiency. Based on this, Hypothesis H3 is proposed:

H3. *Green transformation enhances corporate green investment efficiency by reducing labor employment.*

2.3. The Moderating Role of Digital Transformation

Technological Change Theory and Information Processing Theory together explain the moderating effect of digital transformation. Digital technologies represent a new wave of general-purpose technological change that profoundly impacts information processing and decision-making modes. Digital transformation enhances a corporation's capabilities in data collection, analysis, and application through technologies like big data and AI. In the context of green transformation, these enhanced information processing capabilities enable corporations to more accurately monitor resource flows, assess project risks and returns, and optimize investment decisions [11,18]. Therefore, digital transformation can strengthen the positive relationship between green transformation and investment efficiency by improving the precision and responsiveness of green investment management. Corporations with higher levels of digital transformation can better leverage the benefits of green transformation to achieve efficient green investments. Based on this, Hypothesis H4 is proposed:

H4. *Digital transformation positively moderates the relationship between green transformation and corporate green investment efficiency.*

3. Research Design

3.1. Econometric Model

For Hypothesis H1, the following regression model is constructed:

$$Inveff_{i,t} = \alpha_0 + \alpha_1 GTFP_{i,t} + \sum_{j=1}^n \beta_j Control_{i,t,j} + Year_{i,t} + Stkcd_{i,t} + \varepsilon_{i,t}, \quad (1)$$

where *Inveff* (green investment efficiency) serves as the dependent variable, with *Underinv* representing underinvestment in green initiatives and *Overinv* denoting excessive investment. The explanatory variable is green transformation, while *Control* denotes the control variable. Finally, the analysis controls for *Year* and *Stkcd*.

3.2. Variable Definition

- (1) **Dependent Variable:** This study comprehensively considers factors potentially influencing green investment efficiency when measuring corporate green investment efficiency. Building upon Richardson's inefficient investment model, variables such as environmental protection taxes, government environmental subsidies, environmental regulations, and executives' green credentials were incorporated to construct a corporate green investment efficiency model. Environmental protection tax reflects a corporation's compliance costs with environmental regulations, which affects its capital allocation decisions for green projects. Government environmental subsidies directly alleviate financing constraints and enhance the capacity for green investments. These variables are selected as they represent policy-driven financial mechanisms that align corporate green investments with optimal levels under regulatory and support frameworks. This model calculates corporate green investment inefficiency, green investment underinvestment, and green investment overinvestment. The corporate green investment efficiency model is given in Appendix A.1.
- (2) **Explanatory Variable:** The concept of green transformation can be traced back to an academic report [19]. This report emphasized that genuine economic development should prioritize social inclusivity, sustainability, and capacity building, advocating for the advancement of green transition to ensure stakeholder participation and benefit sharing. Green total factor productivity (GTFP) serves as a measure of a corporation's green transformation progress because it embeds environmental constraints within the core of efficiency assessment. This reflects the comprehensive enhancement of a corporation's capacity to balance economic performance with ecological and environmental considerations. An increase in GTFP signifies that corporations are generating greater economic value with reduced resource consumption and lower environmental costs—precisely the fundamental requirement of green transformation. The DEA framework [20] constructs a Global Production Technology Set and calculates the GML index. The input and output indicators used to measure GTFP are given in Appendix A.2.
- (3) **Control Variables:** corporate size (Size), ownership structure (SOE), debt-to-asset ratio (Lev), return on assets (ROA), cash flow ratio (Cashflow), corporate growth (Growth), proportion of independent directors (Indep), dual role (Dual), top ten shareholder ownership (Top10), and corporate age (CorpAge).
- (4) **Mediating Variable:** corporate uncertainty perception and corporate labor employment.
- (5) **Moderator Variable:** digital transformation.

Variable definitions are presented in Table 2.

Table 2. Variable Definition.

Variable Type	Variable Name	Symbol	Variable Definition
Dependent Variable	Green Investment Efficiency	Inveff	residuals from the Richardson-based green investment model, measuring inefficiency;
		Underinv Overinv	absolute value used for overall efficiency level negative residuals indicating underinvestment positive residuals indicating overinvestment
Explanatory Variable	Green Transformation	GTFP	green Total Factor Productivity measured via GML index
Mediating Variable	Uncertainty Perception Labor Employment	Uword Employee	frequency of uncertain terms in annual reports ln(number of employees + 1)
Moderator Variable	Digital Transformation	DIG	ln(frequency of digital transformation terminology + 1)
Control Variable	Corporate Scale	Size	logarithm of total assets
	Nature of Ownership	SOE	state-owned: 1; non-state-owned: 0
	Debt-to-Asset Ratio	Lev	total liabilities at year-end/total assets at year-end
	Return on Assets	ROA	net profit/total assets
	Cash Flow Ratio	Cashflow	net cash flow from operating activities/total assets
	Corporate Growth Potential	Growth	current year operating revenue/previous year operating revenue − 1
	Percentage of Independent Directors	Indep	ratio of independent directors to total directors
	Combined Position	Dual	are the chairman and general manager the same person? 0: No; 1: Yes
	Top Ten Shareholders' Shareholding Ratios	Top10	percentage of shares held by top ten shareholders
	Corporate Age	CorpAge	ln(observed_year − founded_year + 1)

3.3. Data Source and Descriptive Statistics

This study uses data from all A-share listed corporations in China between 2007 and 2022 as the initial sample. The year 2007 was chosen because it coincides with China's major accounting standards reform, which improved data comparability, and precedes the 2008 implementation of mandatory corporate environmental disclosure policies—both critical institutional shifts directly relevant to measuring corporate green transformation and investment.

The data primarily originates from the Guotai An (CSMAR) database, the China National Research Data Service Platform (CNRDS), the China Environmental Statistical Yearbook, the China Energy Statistical Yearbook, the China Urban Statistical Yearbook, the Civil Affairs Statistical Yearbook, the China General Social Survey (CGSS), the annual reports of listed corporations, and Sina Finance. Additionally, the sample underwent the following screening: (1) exclusion of samples from corporations labeled ST, *ST or PT, or those delisted; (2) exclusion of samples from the financial sector; (3) exclusion of samples with outliers or missing data. To mitigate the impact of extreme values on the regression results, all continuous variables underwent 1% percentile Winsorisation, yielding 19,492 final observations. Descriptive statistics for the variables are presented in Table 3.

Table 3. Descriptive Statistics.

Variable	Obs	Mean	SD	Min	Median	Max
Inveff	19,492	0.052	0.059	0.001	0.031	0.312
GTFP	19,492	1.005	0.038	0.846	1.002	1.177
Size	19,492	22.441	1.332	20.172	22.233	26.449
Lev	19,492	0.434	0.199	0.062	0.430	0.883
Cashflow	19,492	0.051	0.064	−0.125	0.049	0.233
SOE	19,492	0.412	0.492	0.000	0.000	1.000
ROA	19,492	0.043	0.059	−0.179	0.039	0.218

Table 3. *Cont.*

Variable	Obs	Mean	SD	Min	Median	Max
Growth	19,492	0.159	0.332	−0.475	0.108	1.844
Indep	19,492	37.484	5.372	33.330	33.330	57.140
Dual	19,492	0.247	0.432	0.000	0.000	1.000
Top10	19,492	58.090	15.055	24.017	58.518	90.603
CorpAge	19,492	2.918	0.331	1.792	2.944	3.526

4. Empirical Analysis

4.1. Benchmark Regression Results Analysis

Table 4 reports the benchmark regression results for GTFP in relation to Inveff, Underinv, and Overinv. Column (1) shows that the regression coefficient for GTFP is significantly negative at the 5% significance level. This indicates that GTFP improvements enhance overall investment efficiency and reduce inefficient investment. As a corporation's green productivity level increases, its resource allocation becomes more efficient, and management makes more prudent and rational investment decisions, avoiding blind capital expansion or idle resources.

Table 4. Benchmark Regression Results.

Variable	(1) Inveff	(2) Underinv	(3) Overinv
GTFP	−0.025 ** (0.012)	−0.022 ** (0.011)	−0.017 (0.028)
Size	0.002 (0.002)	0.002 (0.001)	0.004 (0.003)
Lev	0.026 *** (0.007)	0.012 ** (0.006)	0.033 ** (0.014)
Cashflow	−0.047 *** (0.008)	−0.030 *** (0.008)	−0.086 *** (0.019)
SOE	−0.010 *** (0.004)	−0.006 (0.004)	−0.017 ** (0.007)
ROA	0.022 * (0.012)	0.008 (0.010)	0.030 (0.028)
Growth	−0.001 (0.001)	0.004 *** (0.002)	−0.007 ** (0.003)
Indep	−0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)
Dual	−0.000 (0.002)	0.001 (0.002)	−0.005 (0.003)
Top10	0.000 ** (0.000)	0.000 *** (0.000)	0.000 (0.000)
CorpAge	−0.018 (0.011)	−0.020 ** (0.009)	−0.021 (0.021)
_cons	0.067 (0.048)	0.064 (0.042)	0.060 (0.101)
FE	YES	YES	YES
N	19,492	12,203	7289
R_a^2	0.240	0.194	0.226

Standard errors are shown in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Furthermore, examining the results in columns (2) and (3), the regression coefficient for GTFP on underinvestment is −0.022, which is significantly negative at the 5% level. This confirms that improvements in green productivity help alleviate corporate underinvestment. In contrast, the coefficient for overinvestment is −0.017—negative but not statistically significant—suggesting that green productivity exerts a relatively weak re-

straining effect on excessive investment. Overinvestment often stems from managerial agency issues or excessive expansion motives, which are primarily influenced by corporate governance structures and internal incentive mechanisms, making it difficult for green productivity improvements to constrain overinvestment directly. Additionally, under green policy incentives, corporate efforts to enhance GTFP usually entail green technology upgrades and increased capital investment, which to some extent mitigates the unidirectional suppression effect on overinvestment. Finally, the relatively small sample size for overinvestment limited the statistical power, resulting in non-significant regression results for GTFP on overinvestment.

This discrepancy suggests that green technological progress primarily addresses underinvestment by alleviating financing constraints and enhancing resource efficiency. However, its role in curbing overinvestment may be undermined by managerial overconfidence or policy incentives. Based on the above analysis, Hypotheses H1, H1a, and H1b are supported.

4.2. Robustness Test

Propensity Score Matching

Currently, China's corporate green transformation is still in its early stages. The varying extent of green transformation among different corporations can result in significant differences in their fundamental characteristics, leading to biases in the assessment of green investment efficiency. To address this challenge, this study uses propensity score matching to balance and adjust the fundamental characteristics of corporations with different levels of green transformation.

Following the methodology of [21], kernel matching tests with a caliper set to 0.01 are employed to ensure precise matching while enabling repeated sampling to improve flexibility. In terms of sample classification, corporations with a green transformation level above the mean are defined as high green transformation samples (assigned a value of 1), while the remaining corporations are categorized as low green transformation samples (assigned a value of 0). In selecting matching variables, this paper fully incorporates core control variables including Size, SOE, Lev, ROA, and Cashflow. All these variables are sourced from the corresponding tables, thereby ensuring the comprehensiveness and accuracy of the matching process.

As shown in columns (1) to (3) of Table 5, the regression results reveal that GTFP exhibits a negative correlation with Inveff and Underinv at the 5% significance level, while Overinv remains insignificant. This indicates that, after effectively controlling for sample selection bias, the extent of corporate green transformation still plays a significant role in reducing green investment inefficiency and mitigating insufficient green investment. This result is highly consistent with Hypothesis H1. Results of other robustness tests, such as the Lag Effect Test and Instrumental Variable Method, are presented in Appendix A.3.

Table 5. Propensity Score Matching Results.

Variable	(1) Inveff	(2) Underinv	(3) Overinv
GTFP	−0.025 ** (0.012)	−0.022 ** (0.011)	−0.017 (0.028)
Control	YES	YES	YES
_cons	0.067 (0.048)	0.064 (0.043)	0.060 (0.101)
FE	YES	YES	YES
N	19,489	12,200	7289
R_a^2	0.240	0.194	0.226

Standard errors are shown in parentheses, ** $p < 0.05$.

4.3. Heterogeneity Analysis

The heterogeneity analysis explores how institutional and corporation-specific contextual factors shape the relationship between green transformation and corporate green investment efficiency. Theoretically rooted in institutional and contingency perspectives—which emphasize that corporate outcomes are contingent on contextual variables—this analysis is empirically motivated by the institutional diversity observed across economies, not just China. Such diversity, including regional development gaps, ownership-based institutional variations, internal governance differences, and industry-specific regulatory landscapes, is a global phenomenon that influences how corporations translate green strategies into investment efficiency.

The four dimensions—region, ownership, agency cost, and industry attribute—were selected for their theoretical significance and cross-border relevance. Regional heterogeneity reflects universal spatial disparities in economic development, policy implementation intensity, and market maturity, which are not unique to China but observable in economies worldwide. Ownership structure captures fundamental differences between state-owned and non-state-owned corporations in resource access, governance objectives, and policy responsiveness—dynamics present in both emerging and developed markets. Agency cost heterogeneity directly tests how internal governance effectiveness moderates the translation of green strategies into efficient investment decisions, a core issue in corporate finance globally. Industry attributes reveal how sector-specific regulatory pressures and technological characteristics differently impact green transformation trajectories, a common pattern across industries regardless of geographic location. Collectively, these dimensions provide a comprehensive framework for understanding how external environments, internal governance, and sectoral contexts jointly influence the effectiveness of corporate green transformation globally.

4.3.1. Region Heterogeneity

The observed regional disparities in the effects of green transformation are intrinsically linked to the geographical clustering of industrial types, a widespread economic phenomenon rather than a China-specific one. Historically, economic development policies globally have led to distinct industrial landscapes: more developed regions tend to concentrate technology-intensive and service-oriented corporations, while less developed regions retain stronger bases in resource-intensive and heavy-polluting industries. This spatial variation in industrial structure implies that regional differences in the results reflect not only place-based institutional factors—such as policy enforcement intensity and market maturity—but also fundamental differences in the transformation capacity and cost structure of corporations across regions worldwide.

Table 6 presents the regression results based on regional heterogeneity (divided by the Hu Huanyong Line, a geographical demarcation reflecting China's regional development divide, which serves as a representative case of global regional disparities). In the more economically developed southeastern region, GTFP has a significantly negative impact on Inveff at the 5% significance level and a significantly negative impact on Underinv at the 10% level. This suggests that for corporations in developed regions, green transformation follows a pattern of “short-term suppression and long-term optimization”—initial efficiency costs give way to improved resource allocation and reduced underinvestment as transformation deepens, a trend consistent with observations in developed economies globally. By contrast, in the less developed northwestern region, GTFP shows no statistically significant impact on Inveff or Underinv, and its coefficient for Inveff is positive. This may be attributed to the region's lower level of economic development and its industrial reliance on resource extraction and heavy manufacturing—challenges faced by less developed regions

across the globe. Here, green transformation is often policy-driven and subsidy-dependent, which may stimulate corporate investment in the short run without yet generating clear efficiency discipline, a common issue in emerging market regions. Regarding Overinv, GTFP coefficients remain insignificant in both regions, indicating that green productivity gains exert limited direct constraint on overinvestment behaviors globally, as these are more strongly influenced by governance and expansion motives.

Table 6. Region Heterogeneity Analysis Results.

Variable	(1) Southeast Inveff	(2) Northwest Inveff	(3) Southeast Underinv	(4) Northwest Underinv	(5) Southeast Overinv	(6) Northwest Overinv
GTFP	−0.026 ** (0.012)	0.053 (0.066)	−0.019 * (0.011)	−0.036 (0.049)	−0.021 (0.028)	0.204 (0.169)
Control _cons	YES 0.067 (0.048)	YES 0.199 (0.339)	YES 0.053 (0.042)	YES 0.336 (0.254)	YES 0.072 (0.102)	YES −0.159 (0.655)
FE	YES	YES	YES	YES	YES	YES
N	18,647	735	11,685	447	6962	288
R_a^2	0.242	0.215	0.200	0.082	0.228	0.220

Standard errors are shown in parentheses, * $p < 0.10$, ** $p < 0.05$.

Thus, the regional heterogeneity identified encapsulates both institutional divergence and industrial-structural variation that are globally relevant, underscoring that corporations operating in less developed, industry-heavy regions—regardless of country—face compounded challenges in translating green transformation into investment efficiency gains.

4.3.2. Property Rights Nature Heterogeneity

Table 7 presents the heterogeneity analysis based on ownership characteristics, a dimension with global relevance given the coexistence of state-owned and non-state-owned corporations in most economies. Notably, the improvement in GTFP of state-owned corporations significantly suppressed both Inveff and Underinv. This suggests that as green productivity increases, the investment decisions of these corporations become more rational, resulting in improved resource allocation efficiency. This outcome may be due to state-owned corporations placing greater emphasis on ecological and environmental performance targets under policy guidance, a tendency observed in state-owned enterprises globally that are tasked with balancing economic and social objectives. As green production efficiency rises, corporations reduce ineffective expansion investments, thereby enhancing capital utilization efficiency.

In contrast, none of the non-state-owned corporation samples reached statistical significance. One possible reason is that non-state-owned corporations usually prioritize short-term profits and returns on capital—a global characteristic of private enterprises. During the process of enhancing green productivity, they often fail to improve investment efficiency significantly due to capital constraints or high environmental governance costs, challenges that private firms face worldwide. Consequently, green productivity gains have not yet been fully translated into optimized investment behavior within these corporations. The coefficients for GTFP were not statistically significant for both state-owned and non-state-owned corporations in terms of Overinv. This suggests that green productivity gains primarily address investment-related inefficiency globally, while their impact on excessive investment driven by agency issues or expansionary impulses is relatively limited. Finally, the heterogeneity of property rights may have a nullifying effect on green productivity in Overinv across economies. While state-owned corporations are constrained by government intervention and investment plans, non-state-owned corporations face market pressures

and financing constraints. The marginal governance effect of green technological progress is limited for both types of corporations globally, rendering it statistically insignificant.

Table 7. Property Rights Nature Heterogeneity Analysis Results.

Variable	(1) State-Owned Corporations Inveff	(2) Non-State-Owned Corporations Inveff	(3) State-Owned Corporations Underinv	(4) Non-State-Owned Corporations Underinv	(5) State-Owned Corporations Overinv	(6) Non-State-Owned Corporations Overinv
GTFP	−0.030 *	−0.024	−0.028 *	−0.015	−0.017	−0.025
	(0.016)	(0.019)	(0.015)	(0.016)	(0.036)	(0.044)
Control	YES	YES	YES	YES	YES	YES
_cons	0.041	0.064	0.022	0.035	0.100	0.077
	(0.081)	(0.061)	(0.070)	(0.051)	(0.169)	(0.140)
FE	YES	YES	YES	YES	YES	YES
N	8034	11,458	5150	7053	2884	4405
R_a^2	0.255	0.237	0.199	0.200	0.258	0.205

Standard errors are shown in parentheses, * $p < 0.10$.

4.3.3. Agency Costs Heterogeneity

Drawing on the methods of [22,23], this paper uses the total asset turnover ratio as a proxy to measure agency costs between shareholders and managers, a core corporate governance issue globally. Table 8 presents the heterogeneity analysis based on agency costs. In the high agency cost group, the regression coefficient for GTFP is negative but not significant. This suggests that when internal agency issues are more severe and management and shareholder objectives diverge more—a universal corporate governance challenge—improvements in green total factor productivity do not significantly improve investment efficiency. By contrast, in the low agency cost groups (columns (2) and (4)), the regression coefficients for GTFP were significantly negative at the 10% significance level. This indicates that in corporations with robust internal governance and milder agency conflicts—regardless of their geographic location—green total factor productivity enhances investment efficiency while curbing excessive investment behavior. The regression coefficients for GTFP in both the high-level and low-level groups failed the significance test for Overinv. This suggests that GTFP has no significant effect on curbing overinvestment behavior globally, and there are no obvious differences between the two groups. These results confirm that GTFP is more effective in addressing underinvestment and enhancing overall investment efficiency than it is in constraining overinvestment driven by expansion motives or agency problems, a pattern consistent with global corporate finance dynamics.

Table 8. Agency Costs Heterogeneity Analysis Results.

Variable	(1) High Inveff	(2) Low Inveff	(3) High Underinv	(4) Low Underinv	(5) High Overinv	(6) Low Overinv
GTFP	−0.022	−0.031 *	−0.022	−0.028 *	−0.039	−0.016
	(0.016)	(0.018)	(0.016)	(0.016)	(0.045)	(0.038)
Control	YES	YES	YES	YES	YES	YES
_cons	0.098	0.114	0.061	0.107 *	0.276 *	0.068
	(0.068)	(0.073)	(0.064)	(0.063)	(0.145)	(0.154)
FE	YES	YES	YES	YES	YES	YES
N	7571	11,921	4912	7291	2659	4630
R_a^2	0.229	0.264	0.203	0.198	0.233	0.256

Standard errors are shown in parentheses, * $p < 0.10$.

4.3.4. Industry Specific Heterogeneity

Table 9 presents the analysis of industry-specific heterogeneity, a dimension with cross-border implications given the global variation in industry regulatory environments and technological characteristics. The findings indicate that in heavily polluting sectors (characterized by stringent environmental regulation and high pollution abatement costs globally), improvements in GTFP have not yet significantly enhanced corporate efficiency. In contrast, GTFP gains can moderately improve corporate efficiency and curb overinvestment behavior in non-heavily polluting industries. The capital-intensive nature of heavily polluting industries and their lengthy technological transformation cycles mean that excessive corporate investment is often driven by long-term strategic planning, policy guidance, and opportunities for capacity expansion—factors common to such industries worldwide—rather than being solely determined by green productivity levels. This weakens the inhibitory effect of GTFP on overinvestment globally. This finding suggests that GTFP primarily influences corporate investment behavior through investment efficiency across industries. However, differences in external financing environments and policy incentives across industries—regardless of country—may hinder the transmission of green transformation effects to investment behavior in heavily polluting sectors, resulting in relatively limited constraints on overinvestment—a form of investment deviation observed globally.

Table 9. Industry Specific Heterogeneity Analysis Results.

Variable	(1) Heavy Pollution Inveff	(2) Non-Heavy Pollution Inveff	(3) Heavy Pollution Underinv	(4) Non-Heavy Pollution Underinv	(5) Heavy Pollution Overinv	(6) Non-Heavy Pollution Overinv
GTFP	−0.012 (0.024)	−0.029 ** (0.013)	−0.023 (0.021)	−0.017 (0.012)	−0.013 (0.059)	−0.022 (0.030)
Control _cons	YES 0.018 (0.080)	YES 0.083 (0.057)	YES 0.038 (0.074)	YES 0.052 (0.046)	YES 0.186 (0.169)	YES 0.091 (0.131)
FE	YES	YES	YES	YES	YES	YES
N	8488	11,004	5222	6981	3266	4023
R_a^2	0.217	0.255	0.161	0.213	0.204	0.251

Standard errors are shown in parentheses, ** $p < 0.05$.

4.4. Mechanism Effect Analysis

To verify whether corporate uncertainty perception (Uword) and corporate labor employment (Employee) mediate the effect of green transformation on corporate green investment efficiency, following the methodology of [24], we construct a mechanism model (Equations (2) and (3)):

$$M_{i,t} = \alpha_0 + \alpha_1 GTFP_{i,t} + \sum_{j=1}^n \beta_j Control_{i,t,j} + Year_{i,t} + Stkcd_{i,t} + \varepsilon_{i,t}, \quad (2)$$

$$Inveff_{i,t} = \vartheta_0 + \vartheta_1 M_{i,t} + \vartheta_2 GTFP_{i,t} + \sum_{j=1}^n \tau_j Control_{i,t,j} + Year_{i,t} + Stkcd_{i,t} + \varepsilon_{i,t}, \quad (3)$$

where $M_{i,t}$ is the mechanism variable, while the meanings of the remaining variables remain consistent with the baseline regression.

4.4.1. Corporate Uncertainty Perception

This paper adopts the methodology of [25] to statistically analyze the frequency of uncertainty-related terms in the Management Discussion and Analysis (MD&A) sections of each listed corporate annual report. These terms include ‘uncertain’, ‘unclear’, ‘ambiguous’,

‘unresolved’, ‘unpredictable’, ‘difficult to estimate’, ‘hard to forecast’, ‘hard to predict’, ‘unforeseeable’, ‘risk’, ‘danger’, ‘crisis’, ‘threat’, and ‘unknown’. The total word count of the MD&A section is then calculated, and the percentage of relevant words relative to the total word count is computed and denoted as ‘Uword’. A higher Uword value indicates greater corporate uncertainty regarding policy changes and shifts in the market environment, while a lower value suggests reduced uncertainty.

The regression results are presented in Table 10 (columns (1)–(4)). The findings suggest that green transformation improves corporate ability to address policy and market risks by enhancing resource allocation efficiency and strengthening green governance capabilities, reducing management’s sensitivity to uncertainties. Even when controlling for Uword, column (2) still shows a statistically significant negative regression coefficient for GTFP at the 5% level. This indicates that the green transition indirectly enhances green investment efficiency by reducing perceived uncertainty. The regression results in columns (3) and (4) align with expectations. These results demonstrate that green transformation directly influences corporate investment behavior through technological progress and productivity gains, and indirectly optimizes the quality of investment decisions by enhancing corporate expectations regarding the external environment, thereby promoting GTFP improvement. This validates Hypothesis H2.

Table 10. Mediating Effect Test Results.

Variable	(1) Uword	(2) Inveff	(3) Underinv	(4) Overinv	(5) Employee	(6) Inveff	(7) Underinv	(8) Overinv
GTFP	−0.046 ** (0.022)	−0.027 ** (0.012)	−0.019 * (0.011)	−0.023 (0.028)	−0.228 ** (0.116)	−0.026 ** (0.012)	−0.023 ** (0.011)	−0.017 (0.028)
Uword		−0.015 *** (0.006)	−0.012 ** (0.005)	−0.018 (0.013)				
Employee						−0.006 *** (0.002)	−0.005 *** (0.001)	−0.014 *** (0.004)
Control _cons	YES 0.445 *** (0.076)	YES 0.065 (0.050)	YES 0.055 (0.042)	YES 0.062 (0.105)	YES −7.116 *** (0.610)	YES 0.025 (0.049)	YES 0.030 (0.044)	YES −0.046 (0.105)
FE	YES	YES	YES	YES	YES	YES	YES	YES
N	18,899	18,899	11,824	7075	19,486	19,486	12,201	7285
R _a ²	0.390	0.245	0.199	0.228	0.933	0.241	0.195	0.229

Standard errors are shown in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.4.2. Corporate Labor Employment

This paper adopts the methodology of [26] by using the natural logarithm of the number of employees to measure labor employment levels. A higher Employee value indicates a higher level of labor employment within the corporation, while a lower value indicates the opposite. The results are shown in Table 10 (columns (5)–(8)). Column (5) shows that as the level of green transformation increases, the scale of labor employment in corporations shows a statistically significant downward trend. This reflects the fact that in advancing green transformation, corporations may reduce their reliance on labor by optimizing production processes and introducing green technologies and intelligent equipment, thereby achieving a labor-saving transformation.

After controlling for Employee, columns (6) and (7) show that the regression coefficient of GTFP on Inveff is significantly negative at the 1% level. This suggests that corporate green transformation directly enhances green investment efficiency and reduces investment shortfalls, as well as indirectly promoting investment efficiency by reducing labor employment—demonstrating a significant partial mediation effect. In column (8), the regression coefficient for employee size is −0.014 and is also significantly negative at the

1% level. This indicates that an increase in employee size inhibits excessive investment behavior. A larger workforce may constrain investment expansion by strengthening internal oversight, increasing organizational complexity, and raising decision-making costs, reducing the likelihood of overinvestment. However, in this model, the coefficient for GTFP is no longer significant, suggesting that workforce size may play a stronger mediating role in the impact of green transformation on excessive investment behavior. In summary, green transformation optimizes production methods and human resource allocation, reducing unnecessary labor inputs. This indirectly enhances corporate green investment efficiency and alleviates underinvestment issues, thus validating Hypothesis H3.

The efficacy of capital–labor substitution is structurally conditioned by industry attributes. The sectoral heterogeneity analysis indicates muted effects in heavy-polluting industries, suggesting that their complex, process-integrated production systems may limit modular technology adoption and incremental labor displacement. In contrast, sectors with more discrete or flexible production processes likely experience stronger substitution-driven efficiency gains. Therefore, the observed labor-employment mediation is not uniform but contingent on underlying technical and operational structures across industries.

4.5. Moderation Effect Test

To test for the moderating effect of digital transformation (Hypothesis H4), the following regression model is constructed:

$$Inveff_{i,t} = \vartheta_0 + \vartheta_1 DIG_{i,t} + \vartheta_2 GTFP_{i,t} + \vartheta_3 DIG_{i,t} * GTFP_{i,t} + \sum_{j=1}^n \tau_j Control_{i,t,j} + Year_{i,t} + Stkcd_{i,t} + \varepsilon_{i,t}, \quad (4)$$

where DIG measures corporate digital transformation intensity.

The DIG index is constructed through text analysis of corporate annual reports of A-share listed corporations. We first compiled a keyword dictionary based on prior literature [27], covering five dimensions: artificial intelligence, big data, cloud computing, blockchain, and digital technology applications. Specific terms include “artificial intelligence”, “machine learning”, “data mining”, “cloud platform”, “smart manufacturing”, “digital management system” and so on. Using Python 3.13, we crawled and analyzed all sample annual reports, counting the frequency of these keywords. The resulting term frequencies were then subjected to logarithmic transformation.

To ensure validity, we conducted the following tests: (1) Content validity: the keyword dictionary was reviewed by experts in information systems and corporate strategy; (2) Criterion validity: DIG showed a significant positive correlation with corporate IT investment intensity and the proportion of technical employees; and (3) Construct validity: factor analysis confirmed that the five dimensions load significantly on a single latent factor. These results support the reliability and validity of DIG as a measure of corporate digital transformation intensity.

The regression results are presented in Table 11. The interaction term $GTFP \times DIG$ is significantly negative in both the *Inveff* and *Underinv* regressions, achieving statistical significance at the 5% level. This finding indicates that DIG significantly amplifies the positive impact of GTFP on improving corporate green *Inveff* and mitigating *Underinv*. Specifically, for corporations with a higher degree of digitalization, green transformation is more likely to translate into high-quality investment decisions through mechanisms such as information integration, process optimization, and data-driven decision support. These channels, in turn, reduce the magnitude of inefficient green investment. In the *Overinv* regression, while the coefficient of $GTFP \times DIG$ is negative, it fails to meet conventional significance thresholds. This suggests that digital transformation does not significantly modify the transmission pathway through which green transformation influences corporate overinvestment behavior. Hypothesis H4 is thus confirmed.

Table 11. Moderating Effect Test Results.

Variable	Inveff	Underinv	Overinv
GTFP	−0.035 *** (0.012)	−0.028 *** (0.010)	−0.028 (0.027)
DIG	0.000 (0.000)	−0.000 (0.000)	0.000 (0.000)
GTFP × DIG	−0.002 ** (0.001)	−0.001 ** (0.001)	−0.002 (0.002)
Control	YES	YES	YES
_cons	0.077 (0.049)	0.068 (0.043)	0.077 (0.100)
FE	YES	YES	YES
N	19,492	12,203	7289
R_a^2	0.240	0.194	0.226

Standard errors are shown in parentheses, ** $p < 0.05$, *** $p < 0.01$.

5. Discussion

This study provides robust empirical evidence on the micro-level relationship between green transformation and corporate green investment efficiency. The findings offer significant insights and nuances when contrasted with the existing literature.

Our core result—that green transformation significantly improves overall green investment efficiency primarily by alleviating underinvestment—advances the prevailing discourse. While prior research has largely examined the determinants and scale of green investment at macro or industry levels [5,28], this study shifts the focus to the efficiency of fund allocation at the corporate level. The insignificant effect on overinvestment further refines this understanding, suggesting that green transformation addresses capital shortage problems more effectively than it curbs managerial overexpansion tendencies driven by agency issues. This asymmetry aligns with and extends the arguments of financial intermediation theory and agency theory.

The revealed heterogeneity enriches our understanding of the contextual boundary conditions. The stronger positive effects observed in state-owned corporations and those in eastern regions resonate with literature emphasizing the role of policy support and institutional environment [6]. Conversely, the muted effects for non-state-owned corporations, firms in central-western regions, and heavily polluting industries highlight the significant challenges of structural adjustment and high transition costs, corroborating findings on compliance burdens [29]. This underscores that the green transformation-efficiency nexus is not uniform but is critically shaped by corporate attributes and regional disparities.

Furthermore, the mediation analysis uncovers two pivotal mechanisms: reducing corporate uncertainty perception and optimizing labor employment. These findings bridge the literature on corporate strategic behavior under uncertainty [3] and on the employment effects of technological change [17], offering concrete pathways through which environmental strategy translates into financial efficiency.

Finally, the positive moderating role of digital transformation represents a timely contribution. It empirically validates the synergistic potential between the green and digital transitions—a critical intersection highlighted in emerging but sparse literature [11,18]. This suggests that corporations can leverage digital capabilities to amplify the efficiency gains from their green transformation efforts.

In conclusion, this study moves beyond aggregate analysis to provide a disaggregated, mechanistic, and contextualized examination of how corporate green transformation influences investment efficiency. The findings collectively emphasize the need for targeted and

integrated strategies that address financing constraints, stabilize expectations, manage structural adjustments, and harness digital synergies to truly enhance green investment efficiency.

6. Conclusions and Policy Recommendation

6.1. Conclusions

This study systematically investigates the impact of green transformation on corporate green investment efficiency, yielding three main theoretical contributions.

First, by integrating innovation diffusion theory with an enhanced Richardson model, this research establishes a new theoretical framework linking corporate strategic actions to investment outcomes at the micro level. The finding that green transformation primarily alleviates underinvestment rather than curbing overinvestment provides empirical support for Financial Intermediation Theory while challenging conventional assumptions about symmetric effects, revealing nuanced mechanisms in environmental investment dynamics. Second, this study uncovers two previously underexplored mediating pathways—uncertainty perception reduction and labor structure optimization—that connect green transformation to investment efficiency. These findings bridge behavioral finance perspectives with technological change theory, offering concrete mechanisms through which environmental strategies translate into financial performance improvements and addressing the literature's overemphasis on technological pathways alone. Third, by identifying digital transformation as a positive moderator, this research creates an important theoretical bridge between green and digital transition literature. The demonstrated synergy effect advances information processing theory by showing how digital capabilities amplify the efficiency gains from environmental initiatives, addressing the critical gap in understanding how these two major transformations interact at the corporate level.

Collectively, these contributions move beyond descriptive analysis to provide a mechanistic, contextualized understanding of how corporate green transformation influences investment efficiency, offering targeted insights for both theory development and practical implementation in sustainable business strategy. Future research could employ longitudinal designs or natural experiments to further disentangle the causal direction between green transformation and uncertainty perception. Quasi-experimental settings, such as examining corporations before and after major environmental policy shocks, could help isolate how exogenous changes in transformation pressure influence managerial uncertainty. Additionally, integrating qualitative insights from corporate executives could shed light on the cognitive and strategic processes underlying this relationship.

6.2. Policy Recommendation

Building on these findings, we propose specific implementation pathways to translate research insights into actionable policies.

Regulatory authorities should develop differentiated green finance assessment standards. For state-owned corporations and eastern region leaders, financial support should be linked to year-on-year improvements in green investment efficiency indicators rather than absolute investment amounts. For non-state-owned corporations and central-western firms, establish “first-transformation risk compensation funds” covering 30–40% of initial project validation costs. Financial institutions should be encouraged to develop “efficiency-linked green loan products” where interest rates decrease as investment efficiency improves. Environmental authorities should publish 3-year rolling policy roadmaps detailing upcoming regulatory adjustments, technological roadmap transitions, and subsidy policy changes. An “uncertainty impact assessment and response mechanism” should be established for providing transitional support measures for corporations significantly affected by major policy shifts, such as phased compliance extensions or temporary tax credits.

“Green transformation employment transition plans” should be developed where governments fund 60% of reskilling costs for employees displaced by green technology adoption. Corporations achieving both emission reduction targets and employment stability through workforce restructuring should receive additional tax incentives. Establish industry-specific “green skills training centers” offering certification programs aligned with corporate transformation needs. Develop and disseminate open-source “digital-green integration toolkits” for SMEs, featuring standardized modules for carbon accounting, investment efficiency monitoring, and decision support. Establish sector-specific demonstration projects in key industries, providing detailed implementation blueprints including cost structures, technical specifications, and management processes.

These implementation pathways address the specific challenges identified in the research while providing concrete steps for policy translation. Future research should focus on evaluating the actual effects of such targeted interventions and exploring dynamic adaptation mechanisms in different institutional contexts.

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Appendix A

Appendix A.1. Green Investment Efficiency Model

The corporate green investment efficiency model is expressed as follows in Equation (A1):

$$GIT_{i,t} = \gamma_0 + \gamma_1 Growth_{i,t-1} + \gamma_2 Size_{i,t-1} + \gamma_3 Lev_{i,t-1} + \gamma_4 Cashflow_{i,t-1} + \gamma_5 Listage_{i,t-1} + \gamma_6 Ret_{i,t-1} + \gamma_7 GIT_{i,t-1} + \gamma_8 EPT_{i,t-1} + \gamma_9 GES_{i,t-1} + Year_t + Industry_i + \varepsilon_{i,t}, \quad (A1)$$

where GIT represents the proportion of corporate green investment. This paper aggregates investment expenditure items related to pollution prevention, ecological environment management, green production, etc., from the detailed entries under the “construction in progress” account in the annual reports of listed companies. These items include desulfurization and denitrification projects, wastewater treatment, energy conservation, dust removal, waste gas and residue treatment, environmental management, ecological restoration, clean production, among others. The total green investment expenditure for the year is then divided by the total assets at the end of the period to derive the proportion of corporate green investment. Growth indicates the corporation’s growth potential, Size reflects the corporate scale, Lev represents the corporation’s debt-to-equity ratio, Cashflow signifies the level of cash flow, Listage indicates the duration of the corporation’s listing, Ret denotes the annual return on shares, EPT stands for environmental protection tax, and GES refers to government environmental subsidies.

Appendix A.2. Input and Output Indicators

Table A1 presents the input and output indicators used to measure GTFP. Input variables include capital investment, fixed asset investment, labor, and energy, while

output variables include desired and undesired output. The definition of each variable is provided in Table A1.

Table A1. Input and Output Indicators.

	Variable Name	Variable Connotation
Input Indicators	Capital Investment	Cash paid for the acquisition and construction of property, plant, and equipment, intangible assets, and other long-term assets
	Fixed Asset Investment	Net amount of the original cost of fixed assets after deducting accumulated depreciation and impairment reserves for fixed assets.
	Labor	Number of employees on the payroll (currently employed) of listed corporations disclosed in the annual report
	Energy	The ratio of the product of the total energy consumption in the city where the corporate is located and the corporate main business revenue to the total industrial output value of the prefecture-level city.
Output Indicators	Desired Output	Corporate Main Business Revenue
	Undesired Output	Estimated Emissions of Pollutants (Industrial SO ₂ , Dust, Wastewater)

Appendix A.3. Robustness Test

Appendix A.3.1. Lag Effect Test

Corporate green transformation is a long-term, dynamic process that affects every stage of the value chain, from product design and manufacturing to supply chain management. It requires consistent implementation of green development principles and continuous optimization to achieve genuine transformation goals. To mitigate potential endogeneity issues arising from bidirectional causality and account for possible time lags in the impact of annual report data on corporate green investment efficiency, this study applies first-order lag treatment to the core explanatory variable, ‘green transformation’ (GTFP).

The regression results are presented in Table A2. The findings suggest that the regression results for green total factor productivity with a one-period lag are consistent with previous findings. This indicates that heightened levels of green transformation reduce overall corporate investment efficiency to some extent, even when accounting for time-lag effects. This suggests that advancing green transformation necessitates significant corporate investment in technological upgrades, equipment renewal, and pollution control, which could result in short-term reductions in investment efficiency. However, this outcome also reflects the ‘transformational cost effect’ of green transformation, whereby short-term investment efficiency is suppressed as corporations pursue sustainable development goals. Consequently, the earlier regression results are further validated.

Table A2. Lag Effect Test Results.

Variable	(1) Inveff	(2) Underinv	(3) Overinv
L.GTFP	−0.022 * (0.012)	−0.014 (0.011)	−0.034 (0.030)
Control	YES	YES	YES
_cons	0.069 (0.053)	0.048 (0.048)	0.065 (0.112)
FE	YES	YES	YES
N	16,863	10,606	6257
R_a^2	0.251	0.204	0.249

Standard errors are shown in parentheses, * $p < 0.10$.

Appendix A.3.2. Instrumental Variable Method

When examining the impact of green transformation on corporate green investment efficiency, it is critical to guard against potential endogeneity, particularly the risk of reverse causality. Specifically, the following reverse causal mechanism may be at play: green transformation does not inherently improve corporate green investment efficiency; instead, firms with inherently higher green investment efficiency, owing to their emphasis on environmental protection and sustainable development, tend to exhibit stronger growth potential and operational capabilities. Such advantages render them more willing and capable of proactively advancing their green transformation initiatives.

To more precisely identify the causal relationship between green transformation and corporate green investment efficiency and rule out the confounding effects of such endogeneity factors, this paper adopts the instrumental variable (IV) method to conduct robustness tests. Following the research design of [30], we select the difference between the explanatory variable and the cube of its year-and-industry weighted mean as the instrumental variable, and then employ two-stage least squares (2SLS) regression for model estimation and validation.

The rationale for this instrumental variable selection is based on two key considerations. First, firms within the same industry share similar industrial attributes and face identical market conditions, leading to a certain degree of correlation in their green transformation behaviors. This satisfies the relevance condition (i.e., the instrumental variable is correlated with the endogenous explanatory variable). Second, there is no conclusive empirical evidence indicating that the green transformation of peer firms in the same industry directly affects the green investment efficiency of a given firm. Thus, this instrumental variable largely meets the requirements of the exclusion restriction condition.

The results of the first-stage regression analysis are presented in Table A3. The instrumental variables are significantly correlated with GTFP at the 1% level. The Kleibergen–Paap rk LM statistic is significant, and the Cragg–Donald Wald F and Kleibergen–Paap Wald rk F statistics are both significantly above the empirical threshold of 10. This indicates that there are no issues of underidentification or weak instruments. Furthermore, the insignificant Hansen J statistic confirms the exogeneity of the instrumental variables. In the second-stage regression results, GTFP shows significant effects on both Inveff and Underinv. This indicates that after controlling for potential endogeneity, green transformation remains statistically significant at the 10% level in influencing corporate green investment efficiency, meaning that the advancement of green transformation continues to enhance corporate green investment efficiency. The significant negative effect of GTFP on Underinv suggests that green transformation helps alleviate corporate investment constraints, enabling firms to overcome underinvestment issues and optimize their investment structure. In the re-

gression on Overinv, the coefficient of GTFP is -0.017 but does not pass conventional significance tests, indicating that after strictly controlling for endogeneity, the direct effect of green total factor productivity on curbing corporate overinvestment is relatively limited. These test results demonstrate that the instrumental variables selected in this study are reasonable and reliable, and hypothesis H1 remains valid.

Table A3. Instrument Variable Test Results.

Variable	(1) GTFP	(2) Inveff	(3) GTFP	(4) Underinv	(5) GTFP	(6) Overinv
IV	-0.432^{***} (0.006)		-0.430^{***} (0.007)		-0.431^{***} (0.008)	
GTFP		-0.024^* (0.014)		-0.026^{**} (0.012)		-0.017 (0.032)
Control	YES	YES	YES	YES	YES	YES
Kleibergen-Paap rk LM statistic		464.20 ***		349.14 ***		236.33 ***
Cragg-Donald Wald F statistic		68,403.09		42,769.90		25,788.17
Kleibergen-Paap Wald rk F statistic		5019.38		3559.63		3111.80
Hansen J statistic		0.000		0.000		0.000
FE	YES	YES	YES	YES	YES	YES
N	19,492	19,492	12,203	12,203	7289	7289
R_a^2		0.007		0.007		0.009

Standard errors are shown in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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