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Does greenization pay off? Insights from an economic vitality perspective

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Guo Wu, Tianjing Zhang & Ailin Dong

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Does greenization pay off? Insights from an economic vitality perspective

Abstract

We investigate the benefits of firms' greenization from an economic vitality perspective. Using firm-level data from Chinese listed firms during the period 2013–2023, alongside with a theoretical evaluation of greenization as a way of accumulating green knowledge capital, we assess the impact of greenization on economic vitality related metrics and the underlying mechanisms. The findings reveal that: (1) Greenization significantly enhances various economic vitality metrics, primarily through a cost reduction effect and an ESG enhancement effect; (2) Digital transformation and corporate innovation amplify the positive impact of greenization on economic vitality; (3) Heterogeneity analyses indicate that large firms and high-tech firms derive greater benefits from green strategies; (4) A series of robustness tests confirm the consistency of the findings. We provide implications for policymakers and firms to harness greenization as an environmental and economic strategy.

Keywords: greenization; economic vitality; digital transformation; ESG; corporate innovation

JEL classification codes: L25; O33; Q56

1. Introduction

The global shift towards a low-carbon economy is a critical component in the fight against climate change and the promotion of sustainable development. Green transformation, or greenization, offers a pathway to mitigate these challenges while fostering economic growth. Greenization denotes the integration of environmentally friendly practices into firms' processes. Governments worldwide, including China, have prioritized green transformation through policies such as carbon neutrality targets and green finance initiatives. For firms, greenization represents both a regulatory obligation and an opportunity to enhance competitiveness. However, the mechanisms through which greenization influences firms' long-term economic vitality (EV) remain underexplored, particularly in emerging economies undergoing rapid industrial and digital transitions (Tian et al., 2022; Wang et al., 2023). As firms increasingly adopt green technologies and sustainable practices, understanding how these initiatives translate into economic resilience and competitive advantage becomes crucial. In this study we address this gap by examining the multifaceted impact of greenization on firms' economic vitality, using firm-level evidence from China, a global leader in green transformation efforts (Zhou et al., 2024; Cai et al., 2025).

Understanding the impact of greenization on economic vitality is vital for multiple reasons. First, as economies transition toward sustainability, firms must reconcile environmental compliance with profitability. Greenization's role in driving operational efficiency, innovation, and market competitiveness offers actionable insights for firms navigating this dual mandate. Second, for China and similar economies, greenization is crucial for achieving national climate goals while sustaining growth. China's industrial-heavy structure and reliance on resource-intensive sectors amplify the urgency of identifying pathways that harmonize green practices with economic resilience.

Current studies predominantly focus on short-term operational impacts of greenization, overlooking its multidimensional effects on long-term organizational resilience (Bak and Cheba, 2022; Li and Lin, 2017). Theoretical exploration of the underlying mechanisms remains sparse, besides some studies (Ren et al., 2024; Tang, 2022). Additionally, mixed evidence persists regarding the roles of digital transformation and ESG practices, with limited empirical validation of their synergistic effects (Feng et al., 2024; Wang and Yao, 2024). For instance, while some studies highlight the positive impact of digitalization on green transformation (Peng et al., 2022), others suggest that its benefits are contingent on firm-specific factors (Chen et al., 2023). Similarly, the relationship between ESG

performance and greenization is often debated, with some studies emphasizing its role in attracting green finance (Li et al., 2023), while others slightly query its direct impact on economic outcomes (Zhou et al., 2024). Furthermore, existing literature often neglects the heterogeneity in greenization's impact across different firms.

This study examines the impact of greenization on firms' economic vitality and the underlying dynamics that drive the impact. Using a panel dataset of 4584 Chinese listed firms from the year 2013–2023, we specifically examine the effects of greenization on various economic vitality metrics. We also conduct a series of robustness checks to validate our findings. We further integrate various theoretical frameworks and propose a model by recognizing greenization as a process of accumulating green knowledge capital, to elucidate how greenization reduces costs, enhances ESG performance, and synergizes with digitalization and innovation. Additionally, we address the heterogeneity across firm type and firm size. This study makes several significant contributions to the literature on economics and management. First, we extend the knowledge-based view (KBV) of the firm by conceptualizing '*greenization*' as a strategic process of accumulating an intangible asset '*green knowledge capital*'. We move beyond viewing green initiatives as mere operational practices to theorizing them as a form of knowledge-based investment that drives long-term value. Second, we provide crucial micro-foundations for dynamic capabilities theory and the Porter hypothesis. While these theories posit a positive link between environmental strategy and performance, we identify and empirically validate two specific mechanisms: cost reduction and ESG enhancement. We explain how green knowledge capital translates into enhanced economic vitality. Third, we recognize a mechanism on the synergy between digital transformation and sustainability. We theorize that digitalization acts as a '*knowledge accelerator*' enhancing a firm's ability to generate and deploy green knowledge capital, thereby amplifying its economic returns.

The rest of the article is structured as follows. Section 2 reviews literature on different aspects of green transformation. Section 3 presents theoretical analysis and hypotheses. Section 4 details the model, variables, and data. Section 5 discusses empirical results, robustness checks, mechanisms, and heterogeneity analysis. Section 6 concludes with implications and policy recommendations.

2. Literature review

The first strand of literature on green transformation or greenization converges around theoretical, conceptual,

practical explorations of sustainability transitions, and factors that affect the efficacy of green transformation. Loiseau et al. (2016) first provide an overview of green economy concepts, definitions, and related tools. The authors emphasize the need for a comprehensive approach that integrates diverse theories and tools to advance green economy objectives. Dincer (2016) introduces the concept of '*greenization*', referring to the process of improving traditional energy systems to enhance their environmental, energetic, and economic performance. Amundsen and Hermansen (2021) explore the concept of green transformation as a boundary object, illustrating its adaptability across various policy discourses. Their study of Norwegian primary industries reveals that while the term '*transformation*' is frequently mentioned, its interpretation varies among stakeholders. Regarding factors affecting green transformation, Tian et al. (2022) analyze green credit policies and find that government incentives accelerate green transitions in heavy industries, and this study elicits the role of institutional frameworks. Wang et al. (2023) then link digital transformation to green total factor productivity and demonstrate that data-driven decision-making optimizes resource use and innovation. We also notice that policy and regional factors may be relevant. Zhou et al. (2024) examine environmental policy uncertainty, and the results show that it creates a dilemma for Chinese firms in balancing green investments and short-term profits. Zhuo et al. (2024) highlight regional coordinated development as a driver of green transformation, particularly in major national strategic zones. Cai et al. (2025) recently argue that intelligent manufacturing improves green transformation outcomes, suggesting that institutional support for tech-driven sustainability can mitigate risks. It can be seen that the current literature implied the multifaceted nature of green transformation, with diverse concepts and theories that inform its implementation.

The second strand of literature focuses on green transformation related aspects at the macro-level. Paroussos et al. (2020) demonstrate that access to low-cost finance and technological progress can drive economic growth while reducing greenhouse gas emissions. Similarly, Chowdhury and Tadjoeeddin (2023) argue that borrowing from central banks could facilitate green transformation in developing countries, challenging traditional concerns about inflation. Welfare state structures also play a critical role, shaping who benefits or bears the costs of the transition (Bak & Cheba, 2022). Li and Lin (2017) highlight the importance of enhancing industrial green development and productivity through structural changes and investment in green technologies. Comparatively, Cheba et al. (2022) identify varying approaches to green transformation in the EU, suggesting the need for country-specific policies.

The third strand of literature emphasizes the interplay between greenization and various factors at the micro-level. For

example, one of the key drivers of green transformation is the integration of digital technologies. For example, Feng et al. (2024) demonstrate that digitalization significantly influences the green transformation of enterprises. Digital tools allow companies to enhance operational efficiencies and reduce environmental impacts, which aligns with the broader trend of integrating digital technologies into green innovation strategies (Peng et al., 2022). Moreover, studies also show that firms' green performance is increasingly tied to their ESG strategies. Li et al. (2023) highlight that firms with higher ESG ratings tend to engage more in green innovation. These firms attract more investment and are better positioned to face regulatory pressures, which facilitates their green transformation. Similarly, Wang and Yao (2024) argues that strong ESG practices help firms navigate financial constraints by enabling easier access to green finance, which supports their green initiatives. Ultimately, the combination of digitalization, ESG practices, and innovative technologies like artificial intelligence (AI) and Internet of Things (IoT), as discussed by Cai et al. (2025), would drive green transformation, fostering sustainable development (Chen et al., 2023; Li and Lin, 2017).

In summary, the literature on green transformation explores multifaceted theoretical, macro-, and micro-level factors, including policy frameworks, digitalization, ESG practices, and regional coordination, etc., that drive sustainability transitions. However, we also identify that there are three notable limitations from the existing literature. First, current empirical studies predominantly concentrate on assessing the influence of greenization on short-term operational metrics and overlook its multidimensional effects on organizational capabilities and long-term competitive resilience. Second, there remains a paucity of theoretical exploration into the fundamental mechanisms driving green transformation. We address this by proposing that greenization constitutes a form of knowledge-based capital. Accordingly, we develop a theoretical framework to elucidate how this capital accumulation enhances firms' various metrics. Third, existing findings present mixed and sometimes contradictory conclusions regarding the roles of digital transformation, ESG engagement, and other influencing factors. We aim to systematically examine their underlying mechanisms through both theoretical analysis and empirical validation. Based on the findings, we offer policymakers actionable insights for designing context-specific interventions that amplify the effects of greenization.

3. Theoretical analysis

We first propose that green transformation, also regarded as greenization, increases firms' economic vitality (EV), as implied by various theoretical frameworks and empirical studies. The natural-resource-based view offers a lens for

understanding how firms can leverage unique resources and capabilities to gain a competitive advantage through sustainable practices (Hart, 1995). The view asserts that investments in green initiatives could enhance operational efficiency and improve corporate reputation, and eventually leading to improved financial performance. Empirical evidence robustly supports this view, indicating a positive correlation between green initiatives and key financial metrics such as return on equity and return on assets. According to Bık and Cheba (2022), firms implementing green strategies report reduced operational costs, which then directly translates to higher profitability. Additionally, the adoption of green technologies may help improve Tobin's Q and total factor productivity (TFP), as firms effectively utilize sustainable innovations to optimize resource consumption and streamline their processes (Li & Lin, 2017; Zhang et al., 2025). Building on the proposed positive relationship, we further propose two mechanisms through which greenization influences EV. First, there may exist a cost reduction effect regarding the impact of greenization. The dynamic capabilities theory emphasizes the importance of firms adapting and reconfiguring their resources to respond effectively to environmental challenges, while simultaneously enhancing operational efficiency (Ren et al., 2024). Greenization likely reduces overheads through digitized processes and leaner supply chains, as seen in Chinese resource-based cities where digital integration lowers administrative and production costs (Feng et al., 2024). Such efficiencies free capital for reinvestment, subsequently amplifying productivity (Wang et al., 2023). Second, greenization may also enhance firms' ESG performance. The ESG enhancement effect has a root from the signaling theory, where superior ESG performance mitigates information asymmetry, attracting ethical investors and reducing financing constraints (Tang, 2022; Wang and Yao, 2024). For example, firms with high ESG ratings experience spillover effects, including improved stock returns and access to green financing (Li et al., 2023). Besides, a strong ESG performance can enhance a firm's social image and consumer recognition, leading to increased market share and revenue (Chen et al., 2023). Overall, we propose the following three hypotheses.

Hypothesis 1. *Greenization increases firms' economic vitality.*

Hypothesis 2. *Greenization impacts economic vitality through a cost reduction effect.*

Hypothesis 3. *Greenization impacts economic vitality through an ESG enhancement effect.*

Digital transformation, as a process of integrating digital technologies into all aspects of business operations, has been widely recognized for its potential to enhance organizational efficiency and transparency (Berman, 2012). Digital transformation not only streamlines internal processes but also enables better data management and analysis, which

could be crucial for implementing green measures effectively. For example, advanced data analytics can help identify areas of resource inefficiency and environmental impact, allowing firms to target these areas for improvement (Feng et al., 2024). Moreover, digital platforms facilitate the sharing of information across departments and with external stakeholders, which is essential for the successful implementation of green initiatives (Kraus et al., 2021). By digitizing environmental data and making it accessible to stakeholders, firms can demonstrate their commitment to sustainability and build trust with customers and suppliers (Frank et al., 2019; Xiao et al., 2025). Digital transformation also facilitates collaboration and knowledge sharing among enterprises, suppliers, customers, and other stakeholders, fostering a collective effort towards green transformation (Barrane et al., 2021; Imran et al., 2021). Digital platforms and networks enable the exchange of best practices, innovation ideas, and environmental data, promoting the diffusion of green technologies and practices across industries and sectors. On the other hand, innovation has long been recognized as a key driver of competitive advantage and organizational performance (Chen et al., 2006; Damanpour et al., 1989). In the context of green transformation, innovation could play a critical role in the development and application of green technologies. Firms that foster a culture of innovation are more likely to develop cutting-edge green technologies that can help create new market opportunities and revenue streams for them (Geroski et al., 1993; Ghisetti and Rennings, 2014). Therefore, based on the above analysis, we propose the following two hypotheses.

Hypothesis 4. *Digital transformation strengthens the positive impact of greenization on economic vitality.*

Hypothesis 5. *Innovation strengthens the positive impact of greenization on economic vitality.*

4. Model and data

4.1. Model specification

In this study, we specify the following panel data model to identify the effect of green transformation on firms' economic vitality (EV).

$$EV_{it} = \beta_0 + \beta_1 Greenization_{it} + \beta_2 Controls_{it} + \gamma_i + \lambda_t + \mu_d + \epsilon_{it} \quad (1)$$

Where $Greenization_{it}$ represent the extent of green transformation for firm i at year t , the term EV_{it} denotes a set of metrics (ROA, Tobin's Q, and TFP) that reflect a firm's economic vitality. The three metrics collectively provide insights into how well a firm is functioning in terms of generating value, using resources wisely, and positioning itself for sustainable growth. The term $Controls_{it}$ represents a set of control variables. The firm fixed effects γ_i and year fixed effects λ_t are included. As represented by the term μ_d , we also incorporate industry fixed effects in our econometric

model to control for unobserved industry characteristics that may confound results. Industry fixed effects can be used to account for regulatory environments that vary by industry, which could influence firm behavior independently. For example, a specific environmental regulation in an industry would impact all relevant firms similarly, but this effect would not be captured by firm or year fixed effects alone. Additionally, if firms switch industries, industry fixed effects can accommodate time-varying industry membership. The term ε_{it} denotes the error term.

4.2. Variables

4.2.1. Independent variable

Green transformation involves strategic adjustments in production processes, adoption of environmentally friendly technologies, and alignment with sustainable practices (Bağ and Cheba, 2022; Xu and Liu, 2023; Xie and Qi, 2024; Zhou et al., 2022b). According to Diner (2016), Greenization is often regarded as a development model embracing environmentally friendly practices to minimize environmental impacts while promoting economic growth. Greenization emphasizes that firms innovate in energy conservation, emissions reduction, and resource utilization to achieve harmonious development between the economy and the environment. In general, the two terms are used interchangeably because they share core objectives of integrating sustainability into business operations. We use the variable $Greenization_{it}$ to denote the extent of green transformation of a firm i at year t . Patent data or carbon emissions have been used as proxies for green transformation (Bağ and Cheba, 2022; Zhou et al., 2022a). However, these quantitative metrics may not adequately reflect firms' qualitative efforts (e.g., governance changes, process optimization, stakeholder engagement) regarding green transformation. Based on a textual analysis method (Loughran and McDonald, 2011; Wu et al., 2021), recent studies (Chen et al., 2023; Li, 2024; Xu and Liu, 2023), and the greenization-related keywords used by Zhou et al. (2022b), we also adopt a keyword frequency analysis in firms' annual reports to measure the extent of green transformation. Annual reports reflect strategic priorities, investments, and operational shifts. The value is therefore calculated as the natural logarithm of one plus the frequency of selected keyword terms counted in annual reports. Keywords like 'energy conservation', 'green patents', and 'pollution control' directly signal a firm's green initiatives. We think that keyword analysis can capture both tangible and intangible green efforts made by a firm.

4.2.2. Dependent variable

Economic vitality (EV) refers to a firm's capacity to sustain long-term growth, profitability, and competitiveness while

maintaining resilience. It reflects an overall view of a firm's ability to thrive dynamically. The development goal of a firm is not just about making profits. It could also involve efficiency, market position, managing risks, asset utilization, etc. EV is therefore unlikely be accurately captured by a single metric. Different aspects like profitability, market value, productivity, and financial structure all contribute to economic vitality. In this study, we use three different metrics to collectively provide a balanced view of EV across financial, operational, and strategic dimensions. First, return on assets (ROA) measures how efficiently a firm uses its assets to generate profit, but this metric ignores equity structure. Second, Tobin's Q is the ratio of market value to the replacement cost of assets. Tobin's Q usually indicates market perception. If Tobin's Q is greater than 1, the market value of a firm is higher than its assets, which suggests intangible assets like brand value. Tobin's Q is therefore often regarded as a forward-looking metric and an important indicator of a firm's long-term value. Fourth, total factor productivity (TFP) measures the efficiency of inputs in the production process and it adds the dimension of productivity beyond just financial metrics. Overall, it can be seen that these metrics complement each other and tackle different features, and collectively they reflect EV more accurately than individually.

4.2.3 Control variables

Based on the studies by Chen et al. (2023), Li (2024), Ren et al. (2023), and Zhang et al. (2025), we include the following potential confounding observables to isolate the effect of green transformation. We adjust for confounding factors across operational, financial, and governance dimensions. As can be seen in Appendix Table A1, the selected control variables capture firm size, financial leverage, liquidity, growth potential, governance structure, ownership concentration, and listing maturity. Detailed measurement methods for each control variable are provided. We also conduct variance inflation factor (VIF) tests for multicollinearity caused by potential redundant controls. The VIF tests return an average value of 1.35 for all variables, suggesting the selection is appropriate.

4.3. Data and descriptive statistics

The firm-level panel data used in this study are sourced from the CSMAR Database, which provides comprehensive and publicly available information on all Chinese listed companies, including detailed financial data. The CSMAR database has been used by various studies (Chen et al., 2023; Khurram et al., 2024; Shi et al., 2024; Song et al., 2024). Data on firm patents, specifically the total number of patents granted and applied for, are obtained from the China National Intellectual Property Administration (CNIPA). Environmental, social, and governance (ESG) scores are

sourced from Huazheng ESG Ratings, in line with the existing literature (Li et al., 2023; Wu et al., 2024; Zeng et al., 2024). To mitigate the influence of outliers, all continuous variables are winsorized at the 1% and 99% percentiles. The final sample excludes firms under special Treatment (ST) or particular transfer (PT). Firms with missing data are also excluded. The final dataset comprises 4584 listed firm over the period 2013–2023 and has a total of 26970 valid observations. Table 1 shows the descriptive statistics and reveals characteristics of the variables. The dependent variables are ROA (mean = 0.039), Tobin's Q (mean = 1.890), and TFP (mean = 6.747). Greenization (mean = 2.091) exhibits variation spanning a range (min = 0.000, max = 3.640), reflecting heterogeneity in firms' green transformation. Control variables align with expectations. As shown in Appendix Table A2, the correlation matrix highlights preliminary relationships. For example, greenization displays a statistically significant positive association with TFP ($\rho = 0.238, p < 0.01$), indicating that greener firms tend to achieve higher productivity. It can also be observed that there is no high correlation (greater than 0.7) among control variables, suggesting that multicollinearity issue is unlikely and this is consistent with the VIF test result.

Table 1. Descriptive statistics.

Variable	Observations	Mean	Std	Min	Median	Max
<i>ROA</i>	26,970	0.039	0.061	-0.247	0.038	0.218
<i>Tobin's Q</i>	26,970	1.890	0.942	0.837	1.624	8.137
<i>TFP</i>	26,970	6.747	0.823	5.106	6.632	9.079
<i>Greenization</i>	26,970	2.091	0.761	0.000	2.079	4.111
<i>Size</i>	26,970	22.320	1.278	20.040	22.111	26.365
<i>Lev</i>	26,970	0.413	0.194	0.060	0.406	0.891
<i>Cashflow</i>	26,970	0.050	0.063	-0.132	0.048	0.241
<i>Growth</i>	26,970	0.142	0.335	-0.512	0.093	1.936
<i>Board</i>	26,970	2.106	0.195	1.609	2.197	2.639
<i>Dual</i>	26,970	0.310	0.463	0.000	0.000	1.000
<i>Indep</i>	26,970	0.378	0.054	0.333	0.364	0.571
<i>Topfirst</i>	26,970	0.331	0.145	0.081	0.308	0.722
<i>Age</i>	26,970	2.134	0.788	0.693	2.197	3.401

5. Empirical results

5.1. Baseline regression

Table 2 presents the results of the baseline regression. Columns 1-3 show the estimation results without control variables, while columns 4-6 display the results with control variables added. Meanwhile, we include fixed effects at the year, firm, and industry levels. The regression results indicate that greenization has a significant positive impact

on all three economic vitality (EV) relevant metrics. It can be seen that a one-standard-deviation increase in a firm's greenization efforts is associated with an increase in its ROA of approximately 0.00145, which represents 3.7% of the average firm's ROA in the sample. For large firms in particular, this seemingly modest percentage increase in ROA may translate into a substantial absolute dollar amount in net income. According to the natural-resource-based view (Hart, 1995), firms can gain a competitive advantage by efficiently using natural resources. Greenization often involves the adoption of energy-efficient technologies and sustainable production processes. For example, firms may install advanced equipment that consumes less energy and raw materials, leading to a reduction in production costs. Firms can then allocate more funds to other productive activities, thereby enhancing profitability and productivity. The Porter Hypothesis suggests that environmental regulation and green transformation can lead to innovation and efficiency improvements, which eventually enhance a firm's competitiveness (Porter and Linde, 1995). When a firm is required to reduce its carbon emissions, it may invest in new technologies that not only meet the environmental standards but also improve its production efficiency. New technologies and innovations give firms a competitive edge in the market and could lead to higher Tobin's Q, as the market recognizes the potential value of them. Meanwhile, consumers are increasingly conscious of environmental issues and prefer to purchase products from firms with a good green image (Wu et al., 2015), the increase in demand can lead to higher revenues and profits, and a good green image may help enhance the firm's market value.

Table 2. Baseline regression results.

Variable	(1) ROA	(2) Tobin's Q	(3) TFP	(4) ROA	(5) Tobin's Q	(6) TFP
<i>Greenization</i>	0.0034*** (0.0007)	0.0238*** (0.0091)	0.0426*** (0.0051)	0.0019*** (0.0006)	0.0534*** (0.0086)	0.0107*** (0.0041)
<i>Size</i>				0.0204*** (0.0011)	-0.5002*** (0.0159)	0.3843*** (0.0077)
<i>Lev</i>				-0.1641*** (0.0044)	-0.0705 (0.0526)	0.0180 (0.0283)
<i>Cashflow</i>				0.2221*** (0.0068)	1.1616*** (0.0875)	0.8344*** (0.0408)
<i>Growth</i>				0.0447*** (0.0011)	0.1825*** (0.0130)	0.2458*** (0.0078)
<i>Board</i>				0.0015 (0.0039)	0.1060** (0.0512)	-0.0106 (0.0230)
<i>Dual</i>				0.0023** (0.0010)	-0.0058 (0.0139)	0.0028 (0.0066)
<i>Indep</i>				0.0028 (0.0111)	0.5271*** (0.1514)	-0.0347 (0.0682)

<i>Topfirst</i>				0.0446*** (0.0060)	-0.0337 (0.0850)	-0.0244 (0.0459)
<i>Age</i>				-0.0206*** (0.0014)	0.4681*** (0.0231)	-0.0614*** (0.0101)
<i>Constant</i>	0.0318*** (0.0015)	1.8421*** (0.0191)	6.6651*** (0.0108)	-0.3455*** (0.0255)	11.4778*** (0.3714)	-1.7614*** (0.1791)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26453	26453	26453	26453	26453	26453
Adjusted R ²	0.4155	0.5950	0.8727	0.5827	0.6336	0.9116

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We control the year, firm, and industry fixed effects.

5.2. Robustness tests

5.2.1. Interactive fixed effects

We first include various fixed effects specifications to help address potential endogeneity concerns and ensures the robustness of the relationship between greenization and economic vitality. The results are summarized in Table 3. City fixed effects control for time-invariant characteristics at the city level, such as geographic location, initial economic development, and local institutional quality that might affect both firm greenization decisions and the EV metrics. China's environmental governance follows a distinctive dual-track system where both central and local governments play significant roles. Meanwhile, the city-year interactive fixed effects account for time-varying city-specific shocks or policy changes and may be used to isolate the firm-level greenization effect from broader city-level environmental or economic trends. In the context of China, the city-year fixed effects might be relevant given China's unique environmental policy implementation pattern. Local governments often respond differently to national environmental campaigns and targets, leading to heterogeneous timing and intensity of environmental enforcement across cities. Similarly, the industry-year interactive fixed effects can control for industry-wide policy changes or market conditions that might affect both environmental practices and firm performance within specific sectors. It can be seen from Table 3 that all estimates across columns 1-9 are significantly positive and the findings continue to hold.

5.2.2. Lagged variable approach

To mitigate potential reverse causality concerns, as suggested by some studies (Khatib, 2024; Li and Lin, 2017; Wang et al., 2023), we adopt a lagged variable approach for robustness check by using the one-period lagged values for both

the greenization measure and control variables. The temporal precedence of greenization before EV metrics reduces the possibility that the current firms' outcomes drives green transformation decisions. As shown in Table 4, the estimates regarding the relationship between greenization and economic vitality remains consistent, with the changes of coefficient values being very minor. The robustness of the results to the lagged specification suggests that the relationship between greenization and economic vitality is unlikely driven by contemporaneous endogeneity concerns.

5.2.3. Propensity score matching

We further conduct a robustness check using propensity score matching (PSM). Given the previously observed positive and statistically significant effects of greenization on EV metrics, we aim to test whether the results are driven by any systematic differences in pre-treatment characteristics between firms undergoing greenization and those that did not. Firms are classified into treatment and control groups based on their greenization intensity. Firms with greenization levels above the 50th percentile are assigned to the treatment group, while those below are in the control group. We employ the nearest-neighbor ($k = 2$) matching with a caliper of 0.05 to ensure comparability and then discard observations outside the common support region to minimize extrapolation bias. We check whether the matching procedure has successfully balanced the covariates by comparing the distribution of covariates before and after matching. Figure 1 indicates that standardized bias for covariates have been greatly reduced after matching. Regression analyses are then performed on the matched sample. Table 5 shows that the results regarding the impact of greenization on various EV metrics remain robust.

Table 3. Robustness check (interactive fixed effects).

Variable	(1)	(2)	(3) TFP	(4)	(5)	(6) TFP	(7)	(8)	(9) TFP
	ROA	Tobin's Q		ROA	Tobin's Q		ROA	Tobin's Q	
<i>Greenization</i>	0.0019** *	0.0545***	0.0108** *	0.0018** *	0.0548***	0.0116** *	0.0018** *	0.0518***	0.0117** *
	(0.0006)	(0.0087)	(0.0041)	(0.0006)	(0.0088)	(0.0042)	(0.0006)	(0.0086)	(0.0041)
<i>Size</i>	0.0206** *	-	0.3828** *	0.0211** *	-	0.3868** *	0.0203** *	-	0.3863** *
	(0.0011)	(0.0162)	(0.0079)	(0.0012)	(0.0165)	(0.0080)	(0.0011)	(0.0159)	(0.0079)
<i>Lev</i>	-	-0.0949*	0.0308	-	-0.0784	0.0425	-	-0.0852	0.0054
	0.1629** *			0.1628** *			0.1643** *		
	(0.0044)	(0.0531)	(0.0284)	(0.0045)	(0.0548)	(0.0288)	(0.0043)	(0.0526)	(0.0283)
<i>Cashflow</i>	0.2205** *	1.1603***	0.8308** *	0.2136** *	1.0844***	0.7849** *	0.2183** *	1.1513***	0.8221** *
	(0.0068)	(0.0874)	(0.0408)	(0.0069)	(0.0873)	(0.0405)	(0.0068)	(0.0872)	(0.0409)
<i>Growth</i>	0.0445** *	0.1825***	0.2473** *	0.0443** *	0.1800***	0.2457** *	0.0440** *	0.1761***	0.2423** *
	(0.0011)	(0.0129)	(0.0077)	(0.0011)	(0.0130)	(0.0077)	(0.0011)	(0.0130)	(0.0078)
<i>Board</i>	0.0026	0.1130**	-0.0167	0.0026	0.0731	-0.0059	0.0009	0.0994*	-0.0153
	(0.0039)	(0.0513)	(0.0229)	(0.0040)	(0.0503)	(0.0230)	(0.0039)	(0.0508)	(0.0231)
<i>Dual</i>	0.0023**	-0.0017	0.0008	0.0022**	-0.0028	-0.0008	0.0023**	-0.0063	0.0021
	(0.0010)	(0.0139)	(0.0066)	(0.0011)	(0.0140)	(0.0066)	(0.0010)	(0.0139)	(0.0066)
<i>Indep</i>	0.0059	0.5716***	-0.0582	0.0089	0.4477***	-0.0319	0.0023	0.5106***	-0.0422
	(0.0112)	(0.1513)	(0.0681)	(0.0113)	(0.1477)	(0.0679)	(0.0111)	(0.1505)	(0.0683)
<i>Topfirst</i>	0.0413** *	-0.0291	-0.0224	0.0382** *	-0.1016	-0.0135	0.0448** *	-0.0153	-0.0071
	(0.0060)	(0.0855)	(0.0461)	(0.0062)	(0.0880)	(0.0479)	(0.0060)	(0.0850)	(0.0461)
<i>Age</i>	-	0.4745***	-	-	0.5055***	-	-	0.4763***	-
	0.0210** *		0.0613** *	0.0199** *		0.0562** *	0.0200** *		0.0622** *
	(0.0014)	(0.0232)	(0.0102)	(0.0015)	(0.0238)	(0.0106)	(0.0014)	(0.0236)	(0.0102)
<i>Constant</i>	-	11.5042**	-	-	11.9451**	-	-	11.3386**	-
	0.3515** *	*	1.7126** *	0.3641** *	*	1.8511** *	0.3417** *	*	1.7924** *
	(0.0259)	(0.3782)	(0.1813)	(0.0267)	(0.3810)	(0.1849)	(0.0256)	(0.3715)	(0.1813)
Year/Firm/Industr y FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	No	No	No	No	No	No
City-year interactive FE	No	No	No	Yes	Yes	Yes	No	No	No
Industry-year	No	No	No	No	No	No	Yes	Yes	Yes

interactive FE									
Observations	26431	26431	26431	26431	26431	26431	26453	26453	26453
Adjusted R ²	0.5852	0.6363	0.9125	0.5916	0.6436	0.9161	0.5859	0.6355	0.9124

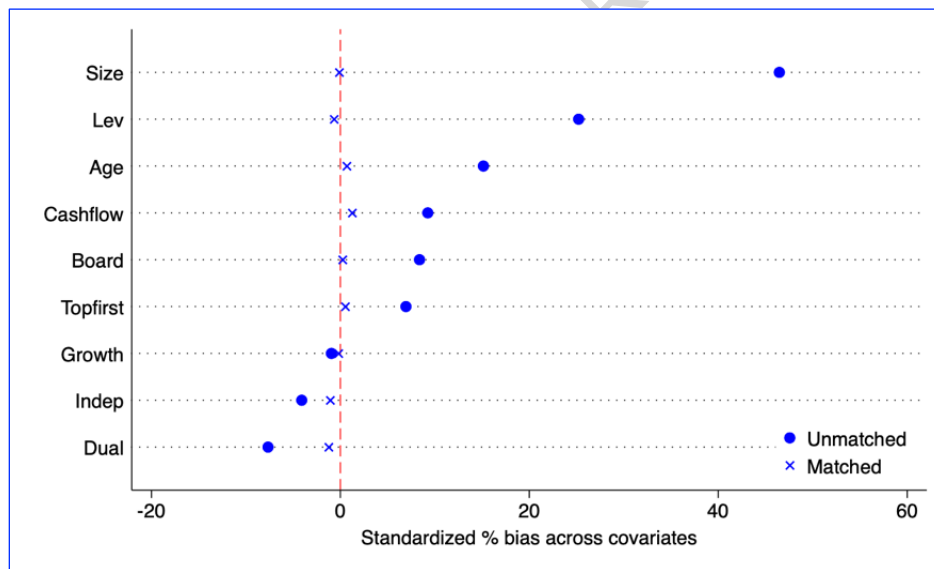
Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; Apart from the year, firm, and industry fixed effects, we also control city fixed effects, city-year interactive fixed effects, and industry-year interactive fixed effects.

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Table 4. Robustness check (lagged variable approach).

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>L.Greenization</i>	0.0013* (0.0008)	0.0260*** (0.0096)	0.0071* (0.0042)
<i>L.Controls</i>	Yes	Yes	Yes
<i>Constant</i>	0.4657*** (0.0386)	10.0815*** (0.4896)	0.9971*** (0.2614)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	20094	20094	20094
Adjusted R ²	0.4701	0.6356	0.9104

Notes: The variable *L.Greenization* denotes the first-order lag of the variable *Greenization*; All control variables are one period lagged (*L.Controls*); The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses.

**Figure 1.** Standardized bias for covariates before and after matching.

Notes: This figure plots the standardized percentage bias for each covariate before and after propensity score matching; The blue dots represent the bias before matching, while the 'x' marks show the substantially reduced bias after matching, indicating that the matching procedure successfully balanced the covariates between the treatment and control groups; The treatment group consists of firms with greenization levels above the sample median, while the control group consists of firms below the median; We employ the logit regression to estimate propensity scores and use a nearest-neighbor ($k=2$) matching algorithm with a caliper of 0.05; Matching is performed only within the common support region to ensure comparability.

Table 5. Robustness check (propensity score matching approach).

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization</i>	0.0020*** (0.0007)	0.0510*** (0.0101)	0.0161*** (0.0050)

<i>Controls</i>	Yes	Yes	Yes
<i>Constant</i>	-0.3666*** (0.0317)	10.5421*** (0.4467)	-1.7964*** (0.2215)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	19463	19463	19463
Adjusted R ²	0.5871	0.6299	0.9078

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We use the nearest-neighbor matching with caliper method; The caliper is set at 0.05 and the neighbor k value is set at 2; We use logit regression and perform matching within the common support range only.

5.2.4 The influence of greenwashing

A potential concern with using textual analysis to measure greenization is that it may capture strategic communication, or "greenwashing" rather than substantive corporate action. To address this, we conduct a series of rigorous tests. First, following the methodology of Hu et al. (2023), we identify and construct a dummy variable for firm-year observations where greenwashing is likely occurring, defined as a mismatch between a firm's environmental disclosures and its actual performance. As can be seen in Table 6, after excluding these observations from our sample, our main findings remain robust and significant, suggesting that our results are driven by genuine greening efforts. Interestingly, we further explore the direct economic consequences of greenwashing itself and find that, for firms that are in the greenwashing group, while it has no effect on short-term profitability, it has a significant negative impact on long-term firm value (Tobin's Q), as suggested by Table 7. This interesting finding indicates that the market ultimately penalizes inauthentic green claims and greenwashing could jeopardize a firm's long-term economic vitality.

Table 6. Robustness check (excluding greenwashing sample).

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization</i>	0.0020*** (0.0007)	0.0590*** (0.0103)	0.0096** (0.0049)
<i>Controls</i>	Yes	Yes	Yes
<i>Constant</i>	-0.3703*** (0.0313)	12.8848*** (0.4504)	-1.8651*** (0.2152)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	20407	20407	20407
Adjusted R ²	0.5689	0.6208	0.8970

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels,

respectively; Robust standard errors are reported in parentheses.

Table 7. The influence of greenwashing.

	(1) ROA	(2) Tobin's Q
<i>Greenization</i>	0.0013 (0.0015)	-0.0387** (0.0171)
<i>Controls</i>	Yes	Yes
<i>Constant</i>	-0.2314*** (0.0790)	10.1481*** (0.8945)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Industry FE	Yes	Yes
Observations	5106	5106
Adjusted R ²	0.6763	0.7213

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses

In fact, the above analysis also demonstrates that Tobin's Q effectively captures whether the market perceives a firm's greenization as a genuine, value-creating strategic investment or as a superficial attempt at reputation management. Considering the sensitivity to greenwashing, Tobin's Q may be the most insightful indicator for assessing the long-term, strategic dimension of economic vitality. Therefore, we further replace our textual-analysis measure with three alternative "action-based" proxies: the number of green invention patents, green utility model patents, and green-related M&A deals. As suggested by Table 8, all three of these tangible measures show a significant positive effect on Tobin's Q, further providing support for our findings.

Table 8. Robustness check (using alternative action-based measures for greenization)

Variable	(1)	(2)	(3)
<i>Green Patent_1</i>	0.0235*** (0.0071)		
<i>Green Patent_2</i>		0.0239*** (0.0070)	
<i>Green M&A</i>			0.0800*** (0.0179)
<i>Controls</i>	Yes	Yes	Yes
<i>Constant</i>	10.1390*** (0.4129)	10.1306*** (0.4135)	11.7502*** (0.7991)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes

Industry FE	Yes	Yes	Yes
Observations	22325	22325	6022
Adjusted R ²	0.6339	0.6339	0.6397

Notes: All control variables (*Controls*) are included; The dependent variable is Tobin's Q; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We measure *Green Patent_1* as the natural logarithm of (1 + the number of invention patents filed), *Green Patent_2* as the natural logarithm of (1 + the number of utility model patents filed), and *Green M&A* as the natural logarithm of (1 + the number of merger & acquisition deals related to green practices), respectively.

Besides, inspired by recent studies and the approaches for measuring corporate supply chain resilience (SCR) (Lin and Li, 2025; Xu et al., 2024; Yuan et al., 2025), we further test the impact of greenization on SCR. China's economy is heavily reliant on manufacturing. SCR is therefore a particularly important indicator for Chinese firms because of the country's central role as a global manufacturing hub with deeply integrated and complex supply chains. SCR may serve as a practical, non-financial measure of economic vitality. According to the results in **Table 9**, we can see that Greenization have a significant and positive effect on SCR. The findings suggest that firms' greening efforts, which often involve optimizing processes and enhancing transparency, contribute to building more resilient and adaptable supply chains. It is evident that the benefits of greenization can extend beyond purely financial performance to core components of long-term organizational resilience.

Table 9. Robustness check (the impact of greenization on corporate supply chain resilience).

	(1) SCR	(2) SCR	(3) SCR
<i>Greenization</i>	0.0578*** (0.0060)	0.0419*** (0.0056)	
<i>L.Greenization</i>			0.0173*** (0.0060)
<i>Controls</i>	No	Yes	Yes
<i>Constant</i>	0.9522*** (0.0124)	-4.4297*** (0.2733)	-4.5166*** (0.3265)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	26308	26308	21669
Adjusted R ²	0.8386	0.8485	0.8605

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses

5.2.5. DID approach

To leverage an external shock, we utilize a quasi-natural experiment based on China's staggered "Low-Carbon City" pilot policy, which was rolled out in three waves in the years 2010, 2012, and 2017. We adopt a staggered difference-in-differences (DID) identification strategy and comparing changes in economic vitality for firms in designated "treatment" cities against those in "control" cities, before and after the policy's implementation. As indicated by Table 10, the DID estimator is positive and statistically significant across all three outcomes. The consistent findings from both the IV and DID approaches provide stronger evidence for a positive relationship between greenization and economic vitality.

Table 10. The results of using a staggered DID design.

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>DID</i>	0.0047*** (0.0010)	0.0583*** (0.0152)	0.0191*** (0.0064)
<i>Controls</i>	Yes	Yes	Yes
<i>Constant</i>	-0.3668*** (0.0290)	-9.9807*** (0.4111)	-1.5522*** (0.2027)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	22324	22324	22324
Adjusted R ²	0.5726	0.6340	0.9125

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses.

5.2.6. Excluding samples from special regions

We also conduct an additional robustness check to account for the potential influence of regional heterogeneity in China. Specifically, firms located in municipalities directly under the central government (Beijing, Shanghai, Tianjin, and Chongqing) and autonomous regions may experience distinct economic and policy conditions compared to those in other provinces. Municipalities, while sharing similar political status with provinces, often benefit from unique economic advantages, such as greater government support, more favorable business environments, and enhanced innovation incentives. Similarly, autonomous regions, which are predominantly minority-populated areas, are subject to distinct geographical, climatic, and economic conditions. They often receive special economic policies from the central government, including tax exemptions or reductions, which may greatly influence firm behavior and

performance. We therefore exclude firms located in the four municipalities and China's autonomous regions from the sample. According to the results shown in Table 11, we find that the positive and statistically significant effects of greenization on ROA and Tobin's Q, supporting the robustness of our findings.

Table 11. Robustness check (excluding special samples).

Variable	(1) ROA	(2) Tobin's Q
<i>Greenization</i>	0.0022*** (0.0007)	0.0510*** (0.0099)
<i>Controls</i>	Yes	Yes
<i>Constant</i>	-0.3466*** (0.0286)	10.9007*** (0.4144)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Industry FE	Yes	Yes
Observations	20690	20690
Adjusted R ²	0.5865	0.6266

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We exclude samples from Chinese municipalities directly under the central government and ethnic minority regions.

5.2.7. Impact of the pandemic

To further ensure the reliability of our findings, we address potential distortions caused by the COVID-19 pandemic. The pandemic has significantly disrupted global economic activities, supply chains, and firm operations. The resulting disruptions may have introduced volatility in firm performance metrics and environmental practices and potentially confounded the relationship between greenization and economic vitality. We exclude all observations from 2020 onward. As can be seen in Table 12, the regression results under the pre-pandemic sample align well with our baseline regression results.

Table 12. Robustness check (excluding the impact of the COVID-19 pandemic).

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization</i>	0.0019** (0.0008)	0.0711*** (0.0119)	0.0136** (0.0056)
<i>Controls</i>	Yes	Yes	Yes
<i>Constant</i>	-0.3170*** (0.0428)	12.7612*** (0.5486)	-0.8666*** (0.3018)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes

Observations	13202	13202	13202
Adjusted R ²	0.5635	0.6570	0.9202

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We exclude samples from the year 2020 and onward.

5.2.8. Influence of national green credit guideline

In this section, we consider split the sample pre- and post-major policy shifts. Specifically, we consider the influence of China's national green credit guideline. We split our sample into two periods: pre-2016 (Panel A) and post-2016 (Panel B), as shown in Table 13. Before the new guideline was established, greenization had a statistically significant and positive impact across all three metrics. In the earlier period, firms' voluntary or early-stage green initiatives were associated with improvements in profitability, long-term value, and productivity. The continued positive impact on Tobin's Q and TFP post-2016 confirms that the market and a firm's underlying productivity still reward green strategies. The loss of significance for ROA is also informative. The result suggests that after 2016, increased pressure may have compelled firms to undertake more substantial and costly green investments. While these investments are valued by the market and improve long-term productivity, their upfront costs might temporarily suppress short-term, accounting-based profitability. Overall, this robustness test supports our overall argument by showing that the benefits of greenization are durable, even if their manifestation shifts from short-term profits to long-term value and efficiency under a new policy regime.

Table 13. Robustness check (the influence of national green credit guideline).

Variable	Panel A: pre-2016			Panel B: post-2016		
	(1) ROA	(2) Tobin's Q	(3) TFP	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization</i>	0.0024** (0.0012)	0.0974*** (0.0259)	0.0198** (0.0095)	0.0011 (0.0007)	0.0250*** (0.0097)	0.0078* (0.0046)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Constant</i>	-0.5028*** (0.0913)	16.4306*** (1.2865)	1.1630 (0.8509)	-0.5053*** (0.0345)	12.2838*** (0.4557)	-1.9172*** (0.2169)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4052	4052	4052	22051	22051	22051
Adjusted R ²	0.7388	0.7051	0.9512	0.6081	0.6667	0.9277

Notes: All control variables (*Controls*) are included; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; Panel A contains sample data before the year 2016; Panel B contains sample data from the year 2016 and onward.

5.3. Mechanism analysis

5.3.1. Cost reduction

We postulate that greenization can enhance economic vitality by optimizing resource allocation and improving operational efficiency, thereby generating significant cost-saving effects. To test this mechanism, we examine the impact of greenization on firms' operational cost. In this study, operational cost refers to all expenses broadly related to business operations, and is proxied by the operating expense ratio from the financial statements. The results are summarized in Table 14. Column 1 suggest that greenization significantly reduces cost. The decline may be associated with reduced agency costs and enhanced operational efficiency (Lu and Wedig, 2013; Sangwan et al., 2024). For example, green technology adoption drives the standardization of production processes and increases resource utilization efficiency. Cleaner production technologies directly compress operational costs by reducing raw material waste and energy consumption (Mostaghimi and Behnamian, 2023). Meanwhile, under the median model specifications, we further find that an increase in the cost significantly reduces ROA, Tobin's Q, and TFP. To formalize the underlying dynamics, we propose a tentative theoretical framework from a resources-reallocation perspective. First, we assume the production function of a firm as Equation 2.

$$Y_t = A_t \cdot (K_t^\alpha L_t^{1-\alpha}) \cdot G_t^\theta \quad (2)$$

Where A_t represent the total factor productivity, K_t denotes capital, L_t denotes labor, and G_t denotes the green knowledge capital accumulated by a firm endogenously through the process of greenization. Green knowledge capital is regarded as a firm-specific, intangible asset that includes the collected technical know-how (Laperche and Liu, 2013), operational methods, and management systems a company uses to reduce its environmental footprint while boosting its economic results. A firm's dynamic capabilities, or its ability to adapt and reconfigure its resources, may be used to leverage this capital (Singh and Rao, 2016). For example, a company might use its green knowledge to identify and act on new green market opportunities. Unlike general knowledge assets such as research and development or marketing expertise, green knowledge capital is exclusively focused on the intersection of environmental sustainability and economic performance.

$$\dot{G}_t = s_G \cdot R_t - \delta G_t \quad (3)$$

In Equation 3, the term \dot{G}_t represents the cumulative green knowledge capital, s_G denotes the efficiency regarding the green knowledge capital, R_t denotes the total R&D capital resources, δ denotes the depreciation rate of green knowledge capital. The cost m has a negative correlation with green knowledge capital, as shown in Equation 4.

$$m_t = m_0 \cdot e^{-\xi G_t}, \xi > 0 \quad (4)$$

$$R_t = \omega Y_t + (m_0 - m_t) Y_t \quad (5)$$

We assume that the saved costs can be converted into available R&D resources, as suggested by Equation 5. The term ωY_t represents a proportion of total output as the regular R&D resources, while the term $(m_0 - m_t) Y_t$ denotes the added R&D resources due to the reduction of cost. Therefore, by combining Equations 4 and 5, we obtain the following equation:

$$R_t = Y_t [\omega + m_0 (1 - e^{-\xi G_t})] \quad (6)$$

It can be seen from Equation 6 that greenization would further increase R&D resources. We test this dynamic empirically using the panel dataset and the regression results are summarized in Table 15. It is revealed that greenization can improve economic vitality through reducing cost and then enhancing R&D resources, validating the cost reduction effect.

Table 14. The cost reduction effect.

Variable	(1) Cost	(2) ROA	(3) Tobin's Q	(4) TFP
<i>Greenization</i>	-0.0021** (0.0009)	0.0017*** (0.0006)	0.0530*** (0.0086)	0.0086** (0.0040)
<i>Cost</i>		-0.0093* (0.0483)	-0.1943* (0.1038)	-0.9931** (0.4092)
<i>Controls</i>	Yes	Yes	Yes	Yes
<i>Constant</i>	0.6818*** (0.0560)	-0.2821*** (0.0379)	11.6103*** (0.3790)	-1.0844*** (0.2952)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Observations	26453	26453	26453	26453
Adjusted R ²	0.7470	0.5935	0.6337	0.9183

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We calculate the cost by dividing the total operational expenses by the total revenue of a firm.

Table 15. The impact of greenization on R&D resources.

Variable	(1) R&D investment	(2) R&D personnel
<i>Greenization</i>	0.0169** (0.0082)	0.0624*** (0.0134)
<i>Controls</i>	Yes	Yes
<i>Constant</i>	-0.4521 (0.3011)	-9.6101*** (0.4508)
Year FE	Yes	Yes

Firm FE	Yes	Yes
Industry FE	Yes	Yes
Observations	26453	26453
Adjusted R ²	0.0306	0.8965

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We use the ratio of capitalized R&D expenditure to net profit to reflect the extent of R&D investment; We measure the level of R&D personnel as the natural logarithm of (1 + the number of R&D personnel).

5.3.2. ESG enhancement

We observe that greenization also enhances ESG performance. Specifically, as shown in Table 16, the mediation model reveals that greenization significantly enhance ESG performance with a coefficient of 0.0187 ($p < 0.01$), and an increase in ESG score would result in the improvement of ROA and TFP, respectively. As discussed in Section 3, one possible underlying dynamic is that firms with high ESG scores build a 'green brand' reputation, gaining consumer preference premiums and investor confidence, as reflected by the statistically significant increase in Tobin's Q value. Another possible dynamic with respect to the ESG mechanism is that firms with ESG advantages are more likely to secure low-cost financing (Bai et al., 2022; Wang and Yao, 2024), such as green bonds which generally have lower issuance rates compared to traditional bonds (Bhutta et al., 2022), and institutional investors usually offer lower pricing discounts for products with higher ESG ratings. In this regard, we may construct the following equation.

$$E_t = E_0 + \kappa G_t \quad (7)$$

$$r_t = r_0 \cdot e^{-\psi E_t} = r_0 \cdot e^{-\psi(E_0 + \kappa G_t)} \quad (8)$$

Where E_t denotes the ESG rating at time t , the parameters $\kappa > 0$ and $\psi > 0$, r_t denotes the interest rate of financing. It can be seen that a higher greenization level G_t would result in a lower value of r_t . To test this dynamic, we examine the relationship between ESG and financing constraint. The empirical results are summarized in Table 17. It is revealed that ESG has a negative impact on the KZ index, signaling that ESG-driven transparency, risk mitigation, and preferential access to green financial instruments enhance fund accessibility for firms with stronger sustainability commitments.

Table 16. The ESG performance enhancement effect.

Variable	(1) ESG	(2) ROA	(3) Tobin's Q	(4) TFP
<i>Greenization</i>	0.0187*** (0.0062)	0.0022*** (0.0007)	0.0621*** (0.0095)	0.0099** (0.0045)
<i>ESG</i>		0.0039*** (0.0009)	0.0226** (0.0114)	0.0158*** (0.0053)

<i>Controls</i>	Yes	Yes	Yes	Yes
<i>Constant</i>	4.7416*** (0.2279)	-0.3335*** (0.0290)	9.8374*** (0.4241)	-1.7092*** (0.2045)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Observations	21763	21763	21763	21763
Adjusted R ²	0.4811	0.5725	0.6339	0.9144

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We use the Huazheng ESG rating scores to measure ESG (Environmental, Social, and Governance) performance, details can be found at the website <https://www.chindices.com/esg-ratings.html>; The ESG scores are derived from a multi-tiered indicator system, and the Chinese A-share listed firms are into levels, ranging from AAA (the highest) to C (the lowest).

Table 17. The impact of ESG rating on financing constraint.

Variable	(1)	(2)
<i>ESG</i>	-0.3050*** (0.0309)	-0.0859*** (0.0195)
<i>Controls</i>	No	Yes
<i>Constant</i>	2.9419*** (0.2267)	12.9487*** (0.7140)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Industry FE	Yes	Yes
Observations	21763	21763
Adjusted R ²	0.6005	0.8267

Notes: The dependent variable is financing constraint; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We use the commonly KZ index (Kaplan and Zingales, 1997) to measure firms' financing constraints.

5.3.3. Digital transformation

Digital transformation represents a fundamental change in how organizations operate and deliver value through the integration of digital technologies (Kraus et al, 2021). Digital transformation enables organizations to enhance their operational efficiency, improve customer experiences, and develop new business models (Berman, 2012). With the integration of advanced digital technologies, digital transformation can enhance the coordination of environmental initiatives across different units in a firm. Better data analytics allow for optimizing resource usage and environmental performance (Ren et al., 2023; Song et al., 2024). Green transformation involves adopting sustainable practices and technologies which could be resource-intensive and complex. Digital transformation may support green initiatives by providing the necessary tools for better data management, process optimization, and innovation. The synergy may

allow firm to achieve enhanced economic vitality. As firms transition towards greener practices, the integration of digital technologies can amplify the positive effects of these practices on their EV metrics. Therefore, we test the moderating effect of digital transformation. In particular, as can be seen in Table 18, the positive and significant interaction terms (*Greenization* \times *Digital*) across all EV metrics indicate that there is a positive moderating effect of digital transformation on the greenization-EV relationship. In other words, firms with higher extent of digital transformation can better leverage their green transformation initiatives to generate superior outcomes. We then extend our theoretical analysis to understand the effect of digital transformation. As studies have provided evidence that digital transformation improves efficiency, the term s_G in Equation 3 can be written as:

$$s_G = s_0 \cdot (1 + \nu D_t), \quad \nu > 0 \quad (9)$$

Where D_t represents the extent of digital transformation and s_0 denotes the level of efficiency without any digital transformation. Equation 3 is then transformed as the following:

$$\dot{G}_t = s_0(1 + \nu D_t)R_t - \delta G_t \quad (10)$$

Combining Equations 4, 6, and 10, when the term \dot{G}_t equals to zero, the green capital reaches the long-term equilibrium value G^* , which is expressed as:

$$G^* = \frac{s_0(1+\nu D)}{\delta} \cdot Y[\omega + m_0(1 - e^{-\xi G^*})] \quad (11)$$

To solve Equation 11, we approximate the exponential term by replacing it with its first-order Taylor expansion, as represented by Equation 12.

$$G^* \approx \frac{s_0(1+\nu D)(\omega+m_0\xi G^*)Y}{\delta} \quad (12)$$

$$G^* = \frac{s_0(1+\nu D)\omega Y}{\delta - s_0(1+\nu D)m_0\xi Y} \quad (13)$$

According to Equation 13, digital transformation D appears simultaneously in both the numerator and the denominator. Digital transformation improves the long-term equilibrium value G^* . Equation 13 suggests that digital transformation could either enhance efficiency through the factor of $1+\nu D$, or strengthening the promotion of resource reallocation by cost savings through the denominator term. This resonates with Equation 4 and the results that greenization reduces cost. We test whether digital transformation enhances the cost reduction effect of greenization. The empirical results in Table 19 further support our proposed mechanism. It should be noted that a moderating effect is usually tested on the full sample to examine how a continuous variable systematically alters the strength or direction of the main relationship, which is often analyzed using an interaction term. In contrast, a heterogeneity analysis typically involves

splitting the sample into distinct sub-groups based on a fixed characteristic to test if the main effect differs between different sub-groups.

Table 18. The impact of digital transformation on economic vitality.

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization × Digital</i>	0.0007** (0.0003)	0.0076* (0.0042)	0.0045** (0.0022)
<i>Greenization</i>	0.0020*** (0.0006)	0.0510*** (0.0087)	0.0110*** (0.0042)
<i>Digital</i>	-0.0001 (0.0004)	0.0270*** (0.0060)	0.0023 (0.0029)
<i>Size</i>	0.0204*** (0.0011)	-0.5079*** (0.0160)	0.3835*** (0.0078)
<i>Lev</i>	-0.1642*** (0.0044)	-0.0628 (0.0526)	0.0183 (0.0282)
<i>Cashflow</i>	0.2222*** (0.0068)	1.1673*** (0.0874)	0.8358*** (0.0408)
<i>Growth</i>	0.0448*** (0.0011)	0.1824*** (0.0130)	0.2463*** (0.0078)
<i>Board</i>	0.0017 (0.0039)	0.1056** (0.0512)	-0.0097 (0.0230)
<i>Dual</i>	0.0023** (0.0010)	-0.0069 (0.0139)	0.0025 (0.0066)
<i>Indep</i>	0.0033 (0.0111)	0.5369*** (0.1515)	-0.0311 (0.0683)
<i>Topfirst</i>	0.0448*** (0.0060)	-0.0338 (0.0848)	-0.0235 (0.0459)
<i>Age</i>	-0.0206*** (0.0014)	0.4682*** (0.0231)	-0.0617*** (0.0101)
<i>Constant</i>	-0.3459*** (0.0256)	11.5892*** (0.3718)	-1.7514*** (0.1796)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	26453	26453	26453
Adjusted R ²	0.5827	0.6339	0.9116

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We follow the approach adopted by existing studies (Jiang et al., 2022; Ren et al., 2023; Wang et al., 2023) to measure the level of digital transformation of a firm.

Table 19. The moderating dynamic of digital transformation.

Variable	(1)	(2)
<i>Greenization</i> × <i>Digital</i>	-0.0013*** (0.0003)	-0.0016*** (0.0005)
<i>Greenization</i>	-0.0022*** (0.0005)	-0.0010** (0.0005)
<i>Digital</i>	-0.0014* (0.0006)	0.0007 (0.0007)
<i>Controls</i>	No	Yes
<i>Constant</i>	0.1677*** (0.0024)	0.6843*** (0.0572)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Industry FE	Yes	Yes
Observations	26453	26453
Adjusted R ²	0.7335	0.7472

Notes: The dependent variable is Cost; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses.

As the above analysis suggests, digital transformation could act as a powerful '*knowledge accelerator*' amplifying the positive economic effects of greenization. By integrating digital technologies, firms can more efficiently create, disseminate, and deploy their green knowledge capital. Digital tools enhance data analytics for resource optimization, improve the coordination of environmental initiatives, and lower the cost of knowledge acquisition. This synergy allows firms to translate their green investments more effectively into superior economic vitality.

5.3.4. Corporate innovation

Corporate innovation refers to a firm's capacity to develop new products, processes, or business models. Innovation enhances a firm's ability to adapt to market changes, optimize resource allocation, and create competitive advantages (Chen et al., 2006; Lengnick-Hall, 1992). When combined with greenization, innovation could act as a catalyst that amplifies the economic benefits of green initiatives. As implied by the views derived from dynamic capability theory (Cavusgil et al., 2007; O'Connor, 2008), innovation can foster agility and allow firms to reconfigure green strategies in response to regulatory, market, or stakeholder pressure. Innovative firms may be better equipped to integrate green technologies into existing processes, which helps sustain long-term competitiveness and ESG alignment. The Porter's Hypothesis also suggests that environmental investments can improve competitiveness through innovation-driven efficiency gains. We therefore test the moderating effect of innovation. As can be in Tables 20 and 21, the *Greenization* × *Innovation* coefficients are consistently positive and significant, signaling that firms with higher innovation levels

experience greater marginal benefits from greenization.

Table 20. The impact of corporate innovation on economic vitality.

Variable	(1) ROA	(2) Tobin's Q	(3) TFP
<i>Greenization</i> × <i>Innovation</i>	0.0006** (0.0003)	0.0074** (0.0036)	0.0072*** (0.0019)
<i>Greenization</i>	0.0019*** (0.0006)	0.0530*** (0.0086)	0.0108*** (0.0042)
<i>Innovation</i>	-0.0008** (0.0004)	0.0015 (0.0054)	-0.0105*** (0.0024)
<i>Size</i>	0.0205*** (0.0011)	-0.5006*** (0.0159)	0.3855*** (0.0078)
<i>Lev</i>	-0.1640*** (0.0044)	-0.0695 (0.0527)	0.0188 (0.0283)
<i>Cashflow</i>	0.2220*** (0.0068)	1.1628*** (0.0875)	0.8329*** (0.0408)
<i>Growth</i>	0.0446*** (0.0011)	0.1825*** (0.0130)	0.2455*** (0.0078)
<i>Board</i>	0.0014 (0.0039)	0.1058** (0.0512)	-0.0120 (0.0230)
<i>Dual</i>	0.0023** (0.0010)	-0.0058 (0.0139)	0.0027 (0.0066)
<i>Indep</i>	0.0026 (0.0111)	0.5232*** (0.1514)	-0.0374 (0.0681)
<i>Topfirst</i>	0.0448*** (0.0060)	-0.0329 (0.0851)	-0.0228 (0.0458)
<i>Age</i>	-0.0207*** (0.0014)	0.4665*** (0.0231)	-0.0628*** (0.0101)
<i>Constant</i>	-0.3455*** (0.0255)	11.4899*** (0.3712)	-1.7626*** (0.1790)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	26453	26453	26453
Adjusted R ²	0.5828	0.6336	0.9117

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; We add 1 to the number of patents applied for by a firm and then take the natural logarithm to indicate the level of innovation.

Table 21. The moderating dynamic of corporate innovation.

Variable	(1)	(2)
<i>Greenization</i> × <i>Innovation</i>	0.0066**	0.0067**

	(0.0027)	(0.0027)
<i>Greenization</i>	0.0281***	0.0235***
	(0.0058)	(0.0058)
<i>Innovation</i>	0.0121***	0.0099***
	(0.0033)	(0.0033)
<i>Controls</i>	No	Yes
<i>Constant</i>	7.2603***	4.5412***
	(0.0135)	(0.2007)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Industry FE	Yes	Yes
<i>N</i>	26453	26453
Adjusted R ²	0.4535	0.4667

Notes: The dependent variable is ESG; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses.

5.4. Heterogeneity analysis

First, as suggested by Table 22, the regression results indicate heterogeneous effects of greenization across firm sizes. For big firms, greenization has statistically significant positive effects on all EV metrics. In contrast, for small-sized firms, the impact of greenization on both ROA and Tobin's Q is not significant, and the regression coefficients are smaller. The impact of greenization on TFP for two groups is similar, as the direct operational efficiency gains from greenization are likely consistent across firms of different sizes. The heterogeneous impact of greenization on ROA and Tobin's Q between big and small firms could be attributed to several factors. For example, from an economies of scale perspective, big firms can better leverage economies of scale in green investments, spreading fixed costs across larger operations and achieving higher gains from environmental innovations. Additionally, within the specific context of China, big firms may possess good policy navigation capability. Specifically, big firms typically have sophisticated government relations departments and better ability to navigate environmental regulations and incentive programs. The close relationship with governments could potentially enable them to better capitalize on green subsidies, tax benefits, and other policy support mechanisms. Second, Table 23 shows the empirical evidence of a disparity in how greenization impacts economic vitality across firm technological orientations. High-tech firms derive relatively large and statistically significant benefits from greenization. Regarding non-high-tech firms, the coefficients are generally smaller, and the effects of greenization on ROA and TFP are even statistically insignificant. The observed heterogeneous pattern strongly corroborates our earlier findings on the moderating effect of innovation. High-tech

firms typically have more developed capabilities for incorporating new technologies and adapting to technological changes. Their existing R&D infrastructure and technological absorptive capacity enable more effective integration and optimization of green-related innovations into their operations, allowing for more efficient green transformation. A company's ability to recognize and use external environmental knowledge is often known as its absorptive capacity (Zahra and George, 2002), which is key to building up its green knowledge capital. In this regard, high-tech firms often have higher absorptive capacities and therefore benefit more from greenization. In addition, from a human capital perspective, high-tech firms generally employ more skilled workers and technical experts who can better understand, implement, and optimize green technologies. The human capital advantage may facilitate more successful green transformation.

Table 22. Heterogeneity induced by firm size.

Variable	Big firms			Small firms		
	(1) ROA	(2) Tobin's Q	(3) TFP	(4) ROA	(5) Tobin's Q	(6) TFP
<i>Greenization</i>	0.0015** (0.0007)	0.0369*** (0.0093)	0.0112** (0.0055)	0.0016 (0.0011)	0.0191 (0.0153)	0.0112* (0.0065)
<i>Size</i>	0.0230*** (0.0017)	-0.2234*** (0.0225)	0.3732*** (0.0123)	0.0325*** (0.0025)	-0.9407*** (0.0329)	0.3482*** (0.0146)
<i>Lev</i>	-0.2051*** (0.0065)	-0.1524** (0.0683)	-0.1295*** (0.0485)	-0.1604*** (0.0071)	0.0513 (0.0824)	0.0835** (0.0370)
<i>Cashflow</i>	0.2122*** (0.0089)	1.0822*** (0.0981)	0.8258*** (0.0572)	0.2080*** (0.0104)	0.9555*** (0.1356)	0.7407*** (0.0536)
<i>Growth</i>	0.0392*** (0.0014)	0.1523*** (0.0140)	0.2252*** (0.0106)	0.0491*** (0.0018)	0.2212*** (0.0217)	0.2598*** (0.0113)
<i>Board</i>	0.0015 (0.0048)	0.1087* (0.0607)	-0.0422 (0.0320)	0.0022 (0.0068)	0.1176 (0.0841)	0.0109 (0.0351)
<i>Dual</i>	0.0016 (0.0014)	-0.0121 (0.0170)	0.0072 (0.0101)	0.0028* (0.0017)	-0.0063 (0.0220)	0.0063 (0.0088)
<i>Indep</i>	0.0001 (0.0001)	0.0059*** (0.0018)	-0.0003 (0.0009)	-0.0000 (0.0002)	0.0022 (0.0025)	-0.0008 (0.0010)
<i>Topfirst</i>	0.0272*** (0.0081)	-0.0600 (0.0867)	-0.0077 (0.0622)	0.0690*** (0.0117)	-0.2626 (0.1711)	-0.0599 (0.0716)
<i>Age</i>	-0.0150*** (0.0024)	0.1901*** (0.0392)	-0.0145 (0.0182)	-0.0322*** (0.0026)	0.8299*** (0.0389)	-0.0772*** (0.0164)
<i>Constant</i>	-0.3944*** (0.0387)	5.8003*** (0.5503)	-1.3717*** (0.2886)	-0.5893*** (0.0546)	20.3822*** (0.7144)	-1.1164*** (0.3139)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Observations	13222	13222	13222	12809	12809	12809
Adjusted R ²	0.6285	0.6798	0.9080	0.5740	0.6130	0.8333

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; The full sample is divided into two groups based on the median of total assets; Firms with total assets above the median are classified as big firms, while those below the median are classified as small firms.

Table 23. Heterogeneity induced by firm type.

Variable	High-tech firms			Non-high-tech firms		
	(1) ROA	(2) Tobin's Q	(3) TFP	(4) ROA	(5) Tobin's Q	(6) TFP
<i>Greenization</i>	0.0030*** (0.0010)	0.0785*** (0.0144)	0.0189*** (0.0063)	0.0008 (0.0008)	0.0333*** (0.0105)	0.0070 (0.0053)
<i>Size</i>	0.0204*** (0.0018)	-0.6291*** (0.0256)	0.3422*** (0.0113)	0.0205*** (0.0015)	-0.4318*** (0.0212)	0.4024*** (0.0108)
<i>Lev</i>	-0.1563*** (0.0067)	-0.0745 (0.0809)	0.1460*** (0.0382)	-0.1730*** (0.0060)	-0.0609 (0.0720)	-0.1253*** (0.0394)
<i>Cashflow</i>	0.2333*** (0.0102)	1.3513*** (0.1395)	0.9067*** (0.0566)	0.2093*** (0.0090)	0.9785*** (0.1091)	0.7423*** (0.0533)
<i>Growth</i>	0.0488*** (0.0017)	0.2213*** (0.0211)	0.2315*** (0.0110)	0.0409*** (0.0015)	0.1494*** (0.0161)	0.2653*** (0.0105)
<i>Board</i>	-0.0002 (0.0063)	0.0696 (0.0709)	-0.0110 (0.0306)	0.0017 (0.0048)	0.1164 (0.0729)	-0.0289 (0.0334)
<i>Dual</i>	0.0004 (0.0016)	-0.0160 (0.0218)	0.0007 (0.0092)	0.0035** (0.0014)	0.0012 (0.0177)	0.0062 (0.0090)
<i>Indep</i>	0.0001 (0.0002)	0.0044* (0.0023)	0.0011 (0.0009)	-0.0000 (0.0001)	0.0054*** (0.0020)	-0.0011 (0.0010)
<i>Topfirst</i>	0.0437*** (0.0100)	-0.2089 (0.1394)	-0.0502 (0.0636)	0.0382*** (0.0077)	0.0156 (0.1104)	0.0262 (0.0608)
<i>Age</i>	-0.0215*** (0.0021)	0.5676*** (0.0364)	-0.0746*** (0.0141)	-0.0195*** (0.0019)	0.4071*** (0.0300)	-0.0458*** (0.0138)
<i>Constant</i>	-0.3500*** (0.0414)	14.3330*** (0.5823)	-0.9599*** (0.2550)	-0.3395*** (0.0341)	9.9864*** (0.5073)	-2.0428*** (0.2535)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12366	12366	12366	14037	14037	14037
Adjusted R ²	0.5805	0.6155	0.8975	0.5939	0.6459	0.9281

Notes: The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively; Robust standard errors are reported in parentheses; According to the classification guidelines issued by China Securities Regulatory Commission (CSRC) in 2012 for Chinese listed firms, firms with industry codes C25-C29, C31-C32, C34-C41, I63-I65, and M73 are defined as high-tech industry firms.

6. Conclusions and implications

6.1. Conclusions

In this study, we examine the relationship between green transformation (greenization) and firms' economic vitality (EV). We specifically uncover key mechanisms and factors that amplify its benefits. Our findings confirm that greenization significantly enhances EV through two primary mechanisms: the cost reduction effect and the ESG enhancement effect. Furthermore, we demonstrate that digital transformation and corporate innovation act as critical moderators, strengthening the positive impact of greenization on EV. These results hold robust across various robustness checks, including the integration of interactive fixed effects, using lagged variables, performing propensity score matching, and the exclusion of special regions or pandemic-affected periods. The findings remain consistent. Our analysis also reveals heterogeneous effects, with larger firms and high-tech firms deriving greater benefits from greenization. By providing insights from an economic vitality perspective regarding greenization, we elicit the dual role of greenization as both an environmental and economic strategy.

From a theoretical standpoint, our study solidifies the relevance of the knowledge-based view for understanding corporate sustainability. By framing greenization as the accumulation of green knowledge capital, we offer a new lens through which to analyze environmental strategy not as a cost center, but as a value-creating investment in intangible assets. Our findings also lend granular, mechanistic support to macro-level theories like the Porter Hypothesis, demonstrating the specific firm-level pathways through which '*doing good*' can translate to '*doing well*'.

6.2. Limitations and future research

While this study provides robust evidence on the positive relationship between greenization and economic vitality, we acknowledge several limitations that also present valuable avenues for future research. First, our primary measure of greenization relies on textual analysis of annual reports. Although we have taken extensive steps to validate this measure and control for the influence of '*greenwashing*', this approach primarily captures a firm's strategic focus and disclosure behavior rather than its substantive actions. Future research could build upon our work by developing composite measures that integrate textual data with objective, physical performance indicators, such as verified carbon emissions, energy consumption data, or pollution abatement investments. Second, while we employ several econometric techniques to mitigate endogeneity and establish causality, we acknowledge the inherent challenges of causal inference in non-experimental settings. Future studies could explore other quasi-natural experiments or use

more granular, project-level data to further strengthen causal claims. Third, our findings are specific to the context of publicly listed firms in China, an economy characterized by strong state guidance and specific national strategies. The mechanisms we identify, particularly those related to policy incentives and the advantages for large firms, may not be directly generalizable to other institutional environments. We think that research comparing the effects of greenization in state-influenced economies versus more decentralized, market-driven economies would be invaluable for understanding the moderating role of the institutional context.

6.3. Implications

We provide implications for policymakers and firms. First, in order to effectively promote green transformation and maximize its potential for sustainable development, policymakers should take a proactive approach in leveraging the synergistic gains from 'greenization-digitalization-innovation'. We show that the integration of digital technologies into green practices can foster greater efficiency, cost-effectiveness, and innovation, creating a powerful combination for achieving sustainability goals. Policymakers should therefore encourage this synergy through an effective combination.

Meanwhile, we recommend policymakers to adopt positive incentive policies that reward firms for their green innovation efforts. These incentives can take the form of subsidies, tax breaks, or financial support for firms investing in green technologies, particularly those that integrate digital solutions. Moreover, we advocate that policymakers should create a competitive market environment where the performance induced by greenization is recognized and rewarded, thereby aligning economic incentives with environmental goals. For example, policymakers may explore a 'green performance-policy dividend' linkage mechanism, which involves creating policies that link the performance of firms in terms of green innovation to specific policy benefits. We think that these policies will likely incentivize firms to actively pursue sustainable development while ensuring that the benefits of these efforts are tangible and impactful. Second, regarding firms, we posit that they should adopt a holistic approach to green transformation by building a framework that integrates a 'technology-operation-innovation' framework. This framework should focus on the continuous development and application of green technologies, accompanied by efficient operational practices that optimize sustainability outcomes. The operational aspect should include fostering a culture of innovation, where sustainability is embedded into corporate strategy and operational processes. Additionally, as suggested by our empirical results, firms should establish dedicated R&D teams focused on exploring new technologies that enhance environmental performance and reduce costs.

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Declaration of competing interest

None.

Data availability statement

The data are available at Figshare repository (doi: 10.6084/m9.figshare.31439983)

Ethical approval statement

Ethical approval was not required for this study as it analyzed exclusively publicly available secondary data. The research did not involve human participants or animals. The research is observational and analytical. It poses no physical, psychological, social, legal, or economic risks to any individual.

Informed consent statement

Informed consent is not applicable to this study. The research involved a non-interventional, retrospective analysis exclusively based on secondary data obtained from publicly available sources. The study did not involve any direct interaction with, experimentation on, or recruitment of human participants. The research was conducted in China. It also does not involve the processing of personal information as defined by China's Personal Information Protection Law. The data are corporate in nature, pertaining to listed companies as legal entities, and do not contain any personally identifiable information of individuals. No primary data collection methods such as surveys, interviews, or experiments were employed.

Appendix

Table A1. Definition of variables.

Variable type	Variable name	Symbol	Definition
Dependent variable	Return on assets	<i>ROA</i>	The ratio of a firm's net profit to its total assets
	Tobin's Q	<i>Tobin's Q</i>	The ratio of a firm's market value to the replacement cost of its assets
	Total factor productivity	<i>TFP</i>	Total factor productivity measured using the Olley-Pakes (OP) method
Independent variable	Green transformation	<i>Greenization</i>	Calculated as the natural logarithm of one plus the word frequency
Control variable	Asset size	<i>Size</i>	The logarithmic value of year-end total assets
	Debt to asset ratio	<i>Lev</i>	The ratio of total liabilities to total assets
	Cash flow ratio	<i>Cashflow</i>	Operating cash flow divided by end-of-period current liabilities
	Revenue growth rate	<i>Growth</i>	(Current revenue - previous year's revenue) / previous year's revenue
	Board number	<i>Board</i>	The logarithmic value of the total number of board members
	CEO duality	<i>Dual</i>	The value is 1 if CEO and chairman roles are combined, 0 otherwise
	Independent board ratio	<i>Indep</i>	The ratio of independent board members on the board
	Top first shareholder	<i>Topfirst</i>	The proportion of shares held by the largest shareholder
	Years since listing	<i>Age</i>	The logarithmic value of the years since listing

Notes: ROA is an accounting metric that reflect profitability, while Tobin's Q reflects the market's expectations for a company's future development; We adopt the Olley-Pakes (OP) method to measure a firm's total factor productivity, the OP method can address simultaneity and selection biases in production function estimation; Based on an textual analysis approach (Loughran and McDonald, 2011; Wu et al., 2021) and the keyword terms described by Zhou et al. (2022b), the level of involvement of a firm in green transformation is assessed by analyzing the frequency of words related to environmental sustainability, green practices, or eco-friendly initiatives in its public annual reports.

Table A2. Correlation analysis.

Variable	ROA	Tobin's Q	TFP	Greenization	Size	Lev	Cashflow	Growth	Board	Dual	Indep	Topfirst	Age
<i>ROA</i>	1.000												
<i>Tobin's Q</i>	0.222**	1.000											
<i>TFP</i>	0.112**	0.290**	1.000										
<i>Greenization</i>	0.019**	0.157**	0.238**	1.000									
<i>Size</i>	0.005	0.396**	0.743**	0.278***	1.000								
<i>Lev</i>	0.346**	0.316**	0.464**	0.165***	0.518**	1.000							
<i>Cashflow</i>	0.455**	0.130**	0.095**	0.045***	0.075**	0.154**	1.000						
<i>Growth</i>	0.288**	0.099**	0.122**	-0.004	0.036**	0.045**	0.032**	1.000					
<i>Board</i>	0.012*	0.104**	0.164**	0.039***	0.272**	0.146**	0.033**	0.007	1.000				
<i>Dual</i>	0.034**	0.099**	0.145**	0.043***	0.186**	0.125**	-0.005	0.025**	0.176**	1.000			
<i>Indep</i>	0.016**	0.034**	-0.009	-0.013**	-0.008	0.013*	-0.002	0.011*	0.571**	0.103**	1.000		
<i>Topfirst</i>	0.152**	0.091**	0.140**	0.032***	0.168**	0.028**	0.121**	-0.009	0.016*	0.052**	0.041**	1.000	
<i>Age</i>	0.187**	0.139**	0.371**	0.089***	0.495**	0.349**	0.001	0.090**	0.196**	0.245**	0.033**	0.079**	1.000

Notes: We use the Pearson method to calculate the correlation coefficient matrix; The symbols ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively.

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