

## Article

# Green Manufacturing and the Co-Evolution of Corporate Digitalization and Greening Transformation Systems: Evidence from China's Green Factory Certification

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## Abstract

The collaborative transformation of digitalization and greening has become a core trend for modern enterprises to build sustainable development systems. As a typical voluntary environmental regulation in China, green factory certification plays an important role in promoting the integration of digital technology and green production. Based on the unbalanced panel data of Chinese A-share listed companies from 2012 to 2022, this paper adopts a multi-period difference-in-differences model to empirically investigate the impact, internal mechanisms and heterogeneous characteristics of green factory certification on corporate digital-green collaborative transformation. The results show that green factory certification can significantly boost the level of corporate digital-green synergy, with an average policy effect of 2.07%. Mechanism tests confirm that this policy realizes the dual transformation through four core paths: stimulating green technological innovation, raising public environmental awareness, improving corporate environmental, social, and governance (ESG) performance and easing financing constraints. Heterogeneity analysis indicates that the promotion effect varies distinctly across regions, enterprise life cycles, pollution types and executive backgrounds. This study reveals the systemic logic of voluntary environmental regulation enabling digital-green collaborative transformation, and provides empirical support and targeted policy suggestions for enterprises and governments to accelerate the integrated development of digitalization and greening.

**Keywords:** green factory; green manufacturing; digital transformation; greening transformation; dual transformation; system transformation



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## 1. Introduction

Global environmental change and sustainable development are two important scientific issues and challenges in the 21st century, while climate change, ecological damage, and environmental pollution have become the three major sources of risk hindering sustainable development [1]. Resolving the complex relationship between economy and environment is becoming increasingly important [2,3], and achieving the right balance between industrial growth and environmental impact reduction is pivotal for companies. Green manufacturing, as an emerging industrial trend with achievable, long-term sustainability prospects, can help companies address these challenges at a systemic level. It is an advanced production philosophy that centers on reducing the impact of industrial activities on climate change and other environmental issues by improving business and manufacturing processes and

shifting stakeholder perceptions [4,5]. This philosophy covers the entire life cycle, from raw material selection to product production, use, and disposal, and aims to achieve efficient use of resources and minimize environmental impact. Green factory demonstration projects are a key part of the green manufacturing system and represent the application of green manufacturing concepts in practice. Through the recognition of “green factories,” enterprises not only demonstrate their commitment to environmental protection but also reflect the energy-saving and emission reduction measures taken in the production process and the pursuit of sustainable development. This voluntary environmental regulatory policy provides an innovative path and practice model for promoting dual transformation.

Driven by dual-carbon goals, the fourth industrial revolution presents new opportunities for green manufacturing. Digital technology serves as an innovative tool that enables companies to pursue productivity goals while focusing on resource efficiency [6–8]. Hence, the idea of digital transformation began to take shape. The concept of digital transformation has been widely explored and interpreted in various ways in the academic and business arenas [9]. Bonnet and Westerman (2020) argue that the process involves the use of technological tools to significantly improve a firm’s operational efficiency and market presence [10]. Vial (2021), on the contrary, describes digital transformation as a process of comprehensively integrating information technology [11], computing power, communication systems, and network connectivity, with the aim of comprehensively strengthening the capabilities of organizational entities. Despite the differences in the specific definitions of digital transformation, they collectively emphasize the critical role of digital technologies in optimizing services, facilitating business processes, and creating value [12–14]. This consensus discloses that digital transformation is not merely a straightforward application of technology; rather, it is a multidimensional and cross-sectional innovation process that demands that firms constantly explore and integrate new technologies to guarantee competitiveness and sustainability in a rapidly altering market.

The concepts of digital transformation and greening of enterprises complement each other and together contribute to the practice of sustainable development. Greening transformation embodies the assumption of environmental responsibility, which confronts environmental challenges head-on by adopting low-carbon, energy-saving, and environment-friendly measures. This transformation not only pursues economic benefits but is also committed to reducing energy consumption while maintaining output efficiency and realizing the harmonious coexistence of ecological and social benefits. Greening transformation and upgrading refer to the processes of continuous improvement of resource utilization, gradual reduction in pollutant emissions, and progressive enhancement of sustainable development capability, with their core power coming from green innovation. The theoretical basis of enterprise greening transformation is stakeholder theory, whose fundamental goals are to reflect corporate social responsibility and to maximize social value by reducing pollution, expanding greenness, and lowering carbon to satisfy the common value needs of stakeholders, such as the government, shareholders, employees, customers, suppliers, the environment, the community, and taxpayers. Digital transformation and greening transformation are not isolated processes, and natural connections and synergies exist between them [15–17].

In this context, the identification and practice of “green factories” have become key links in promoting dual transformation. A “green factory” not only represents an innovation in production methods but is also an important symbol for enterprises to realize the deep integration of digitalization and greening. As an effective tool for improving environmental performance [18,19], green factories can integrate advanced information technology and environmental protection technology to promote enterprises to improve production efficiency while reducing energy consumption and emissions and realize the greening and

sustainability of the production process. Consequently, research on the identification of “green factories” and their practices, whether and how they can effectively facilitate the synergistic transformation of enterprises’ digitalization and greening (dualization), and the issues that arise in the course of policy implementation must be conducted immediately. This study analyzes the influencing factors and heterogeneous characteristics of Chinese enterprises in the synergistic transformation of digitalization and greening and reveals the key driving forces affecting the success of the transformation. The results of the study have far-reaching practical value in guiding enterprises in effectively integrating digitalization and greening strategies and accelerating their transformation pace. At the same time, this study offers an empirical basis for government agencies for formulating and optimizing relevant policies to ensure that the policies can be closely aligned with the actual needs of enterprises and for providing support and guidance for their sustainable development.

The main contributions of this study are as follows: First, China’s environmental regulatory framework consists of a combination of government-led mandatory and voluntary policies. However, relatively few studies have been conducted on how voluntary policies impact the synergistic digitalization and greening transformation of firms. This study aims to provide new insights and understandings to enrich the existing literature. It also gives empirical support for exploring the effectiveness of voluntary environmental regulation policies, such as “green factories,” with Chinese characteristics. Second, this study calculates the synergistic transformation of digitalization and greening on the basis of the coupling method of transformation indicators, which enriches the research on digitalization and greening transformation and facilitates our comprehensive understanding of the direct impacts of green manufacturing on both. Third, this study examines the mechanism of green manufacturing on the synergistic transformation of dual-transformation, unveils the “black box” of the influence mechanism, and provides theoretical guidance for the practice of dual transformation. Lastly, this study identifies the heterogeneous factors affecting the effectiveness of policies by combining the behavioral characteristics and industry attributes of different enterprises, such as geographical distribution, life cycle, pollution type, and executive background. It is of great practical value for optimizing the mechanism of identifying “green factories,” enhancing the efficiency of policy implementation, and facilitating the collaborative dual-transformation of enterprises.

The subsequent arrangement of this paper is as follows: The second part is the literature review. The third part presents the theoretical analysis and research hypotheses. The fourth part elucidates the model design and variable selection. The fifth part provides the empirical results and analysis. The sixth part indicates the research results, policy recommendations, and the shortcomings and outlook of this study.

## 2. Literature Review

Traditionally, environmental regulation has been mainly based on a command-and-control approach, which has played a key role in reducing pollution. However, this approach to regulation may increase the burden on firms and regulators and lead to efficiency problems that inhibit firms’ ability to innovate [20], which in turn affects their long-term market competitiveness [21]. To address these problems, Porter offers a different insight from the conventional view, arguing that environmental regulation, if properly designed, not only promotes environmental protection but also enhances the competitiveness of firms [22]. Additional research by Carlson et al. (2000) revealed that firms can efficiently reduce the cost of abiding by these regulations through the adoption of flexible environmental regulations and the utilization of new technologies [23]. Environmental regulations can enhance the performance of a green economy by facilitating digital transformation and technological innovation and upgrading industrial structure [24,25]. Especially in the more

mature stage of economic development, environmental regulation is believed to significantly promote green technology innovation and industrial structure optimization [26,27]. Nonetheless, the existing literature on Porter's hypothesis tends to focus on government-led environmental regulatory policies, while the role of voluntary environmental regulation is underexplored. This bias may overlook the potential competitive advantage that firms may gain when they voluntarily choose to comply with environment-friendly production standards. Therefore, further research is needed to explore how voluntary environmental regulation affects firms' dualization and synergistic transformation.

Voluntary environmental regulation is a type of environmental protection measure spontaneously adopted by firms that encompasses a wide range of practices from entering into voluntary agreements to developing autonomous environmental programs [28,29]. This form of regulation has been widely adopted by the business community worldwide for decades. In the face of the shortcomings of traditional official regulation, such as regulatory corruption or lack of adaptability, voluntary environmental regulation has gained widespread attention for its flexibility and effectiveness [30,31]. It not only provides a platform for enterprises to screen out those who have the conditions to implement green technology innovations and have the will to improve their environmental performance in the long term but also fits the concept of Porter's hypothesis, which advocates that enterprises can realize a win-win situation for the environment and the economy through innovations. The State Council introduced the concept of "green factories" in 2015 and listed the construction of "green factories" as one of the key issues in the "green factory" concept. As the first all-round environmental standard system based on the viewpoint of the full life cycle of enterprises, the "green factory" certification is an innovative application of voluntary environmental regulatory policy in China's institutional environment.

The impact of environmental regulation on green economy performance is being redefined as digital transformation becomes an inevitable trend in business development. Studies have shown that the development of digital technology has a positive impact on the effectiveness of environmental regulation [32]. The application of digital technologies can enhance green performance by increasing the green innovation capacity of enterprises while reducing human intervention. In addition, digital technologies can influence knowledge integration within firms by improving organizational learning and dynamic capabilities to promote green innovation [33,34]. Digital technologies have the potential to become a core asset for corporate green initiatives, acting as a key tool for transforming environmental challenges into business advantages. Therefore, the key lies in integrating these technologies into corporate sustainability strategies and deeply exploring their application potential and value in driving green development. Through such integration, companies cannot only boost resource efficiency and reduce their environmental impact but can also gain competitive advantages focused on innovation and sustainability in the marketplace.

The "dual transformation" proposed in this context is no longer only concerned with the potential enabling capacity of digital transformation for green innovation but more concerned about how enterprises in the digital era can effectively achieve sustainable competitiveness through synergistic transformation between the two and realize the integration of enterprise value creation and green creation. A green factory is an effort by the manufacturing industry to control and reduce its impact on the environment [18]. As an industry benchmark, being selected as a green factory can help enterprises expand their green investment, alleviate their financing constraints, promote green innovation, and significantly improve their environmental, social, and governance (ESG) performance [35]. However, research on how it affects dual transformation remains relatively limited. Whether green manufacturing can enhance the level of dual transformation, how to enhance it, and what

problems exist in the process of policy implementation have not yet received sufficient attention from scholars. Therefore, further analysis of this issue is necessary to fill this gap.

### 3. Theoretical Framework and Hypothesis

#### 3.1. Institutional Context

Against the backdrop of the Chinese government's intention to accelerate the green development of the country's manufacturing industry, in 2015, the Chinese government released *Made in China 2025*. The State Council introduced the concept of "green factories" and listed the construction of "green factories" as a core element of the "Green Manufacturing Project". It deployed the comprehensive promotion of green manufacturing and endeavored to build a green manufacturing system that is highly efficient, clean, low-carbon, and recycling. The Ministry of Industry and Information Technology (MIIT) formally launched the "green factory" recognition system in 2016; it covers the formulation of green evaluation standards, third-party assessment and certification, policy incentives, and continuous supervision and evaluation. The aim is to make "green factories" a "demonstration benchmark for green transformation and upgrading and a leading force in international competition." The green development of the whole industrial chain and product life cycle is promoted. Green factory evaluation is a strategic task proposed by "Made in China 2025" to speed up the construction of a green manufacturing system and an important green industrial policy to promote the green transformation of traditional manufacturing enterprises with demonstration pilot. As a self-motivated environmental regulatory mechanism, the green factory certification program focuses on assessing the performance of enterprises in achieving green evaluation indicators. It adopts dynamic list management to delist enterprises that fail to consistently meet the standards. On the contrary, the policy provides a series of incentives, including administrative approval facilitation, production scheduling flexibility, and tax incentives, to reward those enterprises that have passed the certification. These measures not only promote environment-friendly behaviors among enterprises but also make them a key force in promoting the development of a green manufacturing system.

At this time of increasing globalized competition, digitization and greening are increasingly becoming key forces driving economic and social transformation, providing unprecedented development opportunities for green manufacturing in enterprises. The Chinese government has clearly stated the strategic goal of deeply integrating emerging technologies with green and low-carbon industries, aiming to realize the green transformation of industries and services through innovation drivers. In September 2021, the Chinese government emphasized the role of technologies such as the Internet, big data, AI, and 5G in promoting the development of green and low-carbon industries. In October of the same year, the State Council issued the Peak Carbon Action Plan by 2030, which further emphasized the importance of the integration of digitization, intelligence, and greening in the industrial sector, and put forward measures to strengthen energy conservation and carbon reduction in new infrastructure. In the 14th Five-year Plan period, the Central Committee for Network Security and Informatization proposed the goal of promoting the construction of a green, intelligent, and ecological civilization and emphasized the need for synergistic development of digitalization and greening. Immediately thereafter, MIIT and seven other departments elaborated on a series of action plans from the green upgrading of facilities to energy consumption and carbon emission management. To further promote this process, in November 2022, MIIT, together with four other departments, selected 10 regions as comprehensive dual-chemistry synergy pilots, with the aim of accumulating innovative practices and experiences in the dual-chemistry synergy transformation of enterprises.

Therefore, studying the role of green manufacturing in promoting digital greening synergistic transformation is not only a positive response to the current policy orientation but also an in-depth exploration of how enterprises can achieve sustainable development under the guidance of the new development concept. By analyzing the specific role mechanism of green manufacturing in promoting dual transformation, we can provide transformation strategies for enterprises and decision-making references for policymakers and jointly promote China's economy to move forward in a greener, smarter, and more sustainable direction.

### 3.2. Role of Green Manufacturing in Influencing Dualization Synergies

As a voluntary environmental regulatory policy, the “green factory” accreditation provides direct incentives for enterprises to perform dual transformation in direct coordination with government subsidies and incentivizing policy tools, such as green credits. After enterprises are identified as green factories, the government will provide them with government environmental protection subsidies in the form of one-time awards, industrial transformation, and upgrading funds or special construction fund support, which directly increases the internal funds for the dual transformation of enterprises. “Green factories” can also obtain green credit preferences, such as increased credit limits and decreased interest rates for loans. Indirectly, enterprises certified as “green factories” can send signals to external investors that they consciously fulfill their social responsibilities and thus obtain support from external investors while improving their reputation, enhancing their risk-bearing level, and facilitating the development of “green factories” to engage in dual-transformation activities [36,37]. In consideration of the strict standards for green factory selection, which place clear requirements on corporate green behaviors, and given that companies that do not meet the requirements for green manufacturing demonstration will be removed from the demonstration list, this strong environmental regulatory measure plays a key role in optimizing the environmental behaviors of the companies themselves. To reduce the possibility of being delisted, the selected enterprises will increase the intensity of their green behaviors and actively perform a dualistic and synergistic transformation by improving the efficiency of energy consumption, optimizing the structure of energy use, and adopting more advanced and applicable cleaner production process technologies and equipment [38]. Therefore, this study proposes the following hypotheses:

**H1.** *Green manufacturing will significantly improve the level of dual transformation.*

### 3.3. Mechanism of Green Manufacturing on Dualization Synergy

The growing environmental awareness of young consumers, with a preference for “green” products, is reshaping the market. Businesses understand the importance of their customers and that their needs are critical to their survival and growth. As customers become more environmentally conscious, companies must pay attention and respond to these needs [39]. Customers’ environmental preferences drive companies to incorporate sustainability elements in their products and services. This customer-driven pressure, unlike the hard constraints of government regulation, is a soft constraint that pushes companies to follow ethical norms and social expectations. Companies can be pushed to re-examine their strategies, especially on how they can utilize digital technologies throughout the production process to address environmental challenges while complying with environmental regulations and standards. Such utilization is also an important consideration in their purchasing decisions and motivates firms to invest substantial resources in green management. Therefore, we propose the following hypothesis:

**H2.** *Green manufacturing will enhance the level of dual transformation by increasing public environmental concern.*

The digital economy is bringing unprecedented opportunities for businesses to refine their development, with green innovation playing a central role [15]. Such innovation not only mitigates the impact on the environment but also enhances the market competitiveness of enterprises by optimizing the use of resources and contributes positively to economic growth and social equity. The practice of green innovation emphasizes a sustainable approach to development that closely integrates economic and social needs and environmental responsibility and is committed to developing new products and strategies that significantly reduce environmental impacts. Numerous studies have explored the relationship between environmental regulation and green innovation. The general consensus is that environmental regulations play a positive role in stimulating environment-friendly patents [40]. In addition to environmental regulations, other government policy instruments, such as increased investment in R&D, have likewise been shown to stimulate firms' innovative activities [41]. Bu et al. (2020) show that the adoption of voluntary environmental policies significantly promotes firms' innovations, a finding that further underscores the importance of policy design in stimulating the potential for innovation [42]. Therefore, we propose the following hypothesis:

**H3.** *Green manufacturing will heighten dual transformation by improving green innovation.*

In fact, from the perspective of information disclosure cost, selected green factory demonstration enterprises not only have the opportunity to enjoy the corresponding national policy support, provincial and municipal incentives, financial institutions' preferential interest rate loans, etc., but they also objectively generate additional financing channels, enjoy reduced financing cost [43], and likely obtain the favor of green credit funds, thus alleviating the enterprises' financing constraints. Being selected as a green factory allows an enterprise to become a green benchmark in the industry, and by strengthening its own environmental awareness and actively carrying out green practices, it can promote itself to stakeholders, such as investors, regulators, and potential capital suppliers, to attract positive responses in terms of financing, government subsidies, etc. The policy tools, such as environmental subsidies, tax incentives, and green finance, brought by green manufacturing can improve the level of dual transformation by compensating for the asymmetry between costs and benefits induced by positive externalities of innovation and alleviating the pressure of enterprise innovation funds. Therefore, we propose the following hypothesis:

**H4.** *Green manufacturing will enhance dual transformation development by reducing financing constraints.*

Green manufacturing plays a critical role in improving corporate environmental performance and social responsibility [35]. In recent years, with the ESG concept becoming deeply rooted in people's minds and the public's environmental protection consciousness gradually strengthening, the public's demand for environmental information has been on the rise, and their tolerance for environmental violations has been diminishing [44]. The monitoring role of the public, especially the strong reaction to corporate environmental violations, together with a convenient complaint mechanism, has been shown to be effective in reducing corporate pollution emissions and lowering the incidence of violations. Stronger environmental regulatory requirements likewise imply that firms will be subject to more severe punitive measures when violating environmental protection requirements. To

reduce the punitive costs, they may face as a result of environmental regulations, firms tend to take proactive measures to reduce their negative impacts on the environment. This action not only materially improves their environmental performance but also facilitates significant advances in terms of the quantity and quality of their environmental information disclosures. In this context, firms selected as green factories will pay considerable attention to improving their ESG performance to avoid environmental violations and litigation risks. Accordingly, we propose the following hypothesis:

**H5.** *Green manufacturing will strengthen dual transformation by improving firms' ESG performance.*

## 4. Model Design and Variable Selection

### 4.1. Multiperiod Double-Difference Modeling

Given that the timing of green manufacturing adoption is not uniform across provinces in China, it does not satisfy the applicability conditions of the classical double-difference model, and a multiperiod double-difference model is needed. Therefore, to test the enhancement effect of green manufacturing on dual transformation, i.e., to verify H1, this study draws on the research of Zhu et al. (2023) to construct the following multiperiod double-difference fixed-effect model (1) [45]:

$$dgst_{i,t} = \alpha_1 + \beta_1 post_{i,t} \times policy_{i,t} + \sum_j \beta_j control_{j,i,t} + \mu_i + \lambda_i + \varepsilon_{i,t} \quad (1)$$

where  $i, t$  represent individual firms and year, respectively;  $dgst_{i,t}$  denotes the level of dualization synergy of listed enterprise  $i$  in year  $t$ ; and  $policy$  is a dummy variable for whether the sample firm is selected for the green factory demonstration list. If yes, the  $policy$  is 1, and the value of the previous year is 0. The coefficients of the double-difference term,  $Post$ , are the following ( $\beta_1$ ): The changes in the level of dual transformation of enterprises before and after the "green factory" accreditation are estimated. If the "green factory" accreditation can significantly improve the level of dual-chemistry dual transformation of enterprises, then  $\beta_1$  should be significantly positive.  $control$  is a control variable.  $\mu_i$  denotes individual fixed effects,  $\lambda_i$  denotes year fixed effect, and  $\varepsilon_{i,t}$  is a random disturbance term.

For further analysis on the role of mechanism variables in the influence of green manufacturing on synergistic dual transformation, additional analysis is warranted. This study refers to Chen and Zhang (2023) to establish the following regression model [38]:

$$N_{i,t} = \alpha_1 + \beta_1 post_{i,t} \times policy_{i,t} + \sum_j \beta_j control_{j,i,t} + \mu_i + \lambda_i + \varepsilon_{i,t} \quad (2)$$

where  $N_{i,t}$  represents mechanism variables, including green technology innovation ( $gpatent$ ), public environmental concern ( $public$ ), financing constraint level ( $sa$ ), and ESG level ( $hesg$ ). The coefficients in model (2)  $\beta_1$  reflect the effect of green manufacturing on mechanism variables.

### 4.2. Variable Selection and Description

#### 4.2.1. Explanatory Variable

Digitalization and greening synergistic transformation ( $dgst$ ): The two indicators of digitalization transformation and greening transformation are derived by coupling calculation using the entropy method model. The comprehensive score of the coupling calculation reflects the overall performance of dual transformation. The enterprise digitalization system refers to the existing literature, which uses the statistical perspective of the word frequency of "enterprise digital transformation" in the annual reports of listed enterprises

to portray the degree of transformation. The statistics of 76 digitization-related words in five dimensions, namely, artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and the use of digital technology, are presented. Because this kind of data has the typical characteristic of “right skewedness,” this study will logarithmize it to obtain the overall indexes for portraying the digital transformation. In reference to the study, greening transformation is measured using textual information disclosed in annual reports. The keywords relating to enterprises’ greening transformation are selected based on five aspects: publicity initiatives, strategic concepts, technological innovation, sewage treatment, and monitoring management. Then, the frequency of each keyword in the text of annual reports of listed enterprises is counted to form the word frequency number of greening transformation, and the natural logarithm is taken to portray the greening transformation of enterprises by adding 1 to this word frequency number.

#### 4.2.2. Core Explanatory Variable

Green manufacturing (policy). Drawing on the work of Yang and Rui (2020), this study uses a dummy variable for the green factory identification policy [31]. It indicates whether the factory is recognized as a “green factory”; if yes, it is 1; otherwise, it is 0. Given six batches of green factories selected at different times, differences exist in the enterprises selected in different years. Therefore, the variable is set on the basis of the six batches of green factory demonstration lists published by MIIT from 2012 to 2022. If there exists a green factory selection for listed firm *i* in year *t*, the variable is equal to 1 in year *t* and subsequent years; otherwise, it is 0.

#### 4.2.3. Control Variables

On the basis of the study of Zhou et al. (2023), we control for the following firm-level variables: firm age (age), total gearing ratio (tor), return on net assets (roe), equity concentration (eci), and nature of ownership (soe) [46]. In particular, firm age is an important indicator of firm maturity and experience, which can reflect the accumulation and growth history of the firm in the market by calculating the difference between the firm’s establishment time and listing time. Total gearing ratio is measured as the proportion of total liabilities to total assets, which exhibits the level of financial leverage of the company and is a key indicator for assessing the financial risk and solvency of the company. The return on net assets uses net profit as a percentage of net assets. It is a core indicator of a company’s profitability, reflecting the profitability efficiency of the company’s assets. Equity concentration is an important aspect of corporate governance structure, which affects the decision-making process and risk taking of the company. In this study, the sum of the shareholding ratios of the top five outstanding shareholders of a listed company is used to measure it. The nature of ownership is a dummy variable defined as 1 if the firm is a state-owned enterprise and 0 otherwise.

#### 4.2.4. Mechanism Variables

With reference to the existing literature [47], green technology innovation (gpatent), public environmental concern (public), financing constraints level (sa), and ESG level (hesg) are used as mechanism variables. Among them, green technology innovation is measured by the number of green patent applications of enterprises. Public environmental concern is an important reflection of public environmental preference, which is measured using a prefecture-level Baidu index. The level of financing constraints is determined by the financing constraint index, calculated using the SA method, which is an index that measures the degree of difficulty faced by enterprises in obtaining external financing. The higher this index is, the more constrained the enterprise is in the financing process, and the more difficult it is to obtain funding. The ESG level is measured on the basis of the China

Securities Rating Index. China Securities ESG rating is closer to the Chinese market than other ESG evaluation systems. The rating is divided into nine grades, which are assigned a score of 9–1 in descending order.

#### 4.3. Data Sources and Descriptive Statistics

This study explores the impact of green manufacturing on dual transformation, using Chinese A-share listed companies from 2012 to 2022 as a research sample. The data on green transformation come from the textual analysis of the annual reports of enterprises. The list of “green factories” is from the official website of MIIT, and the data of other companies are from the Cathay Pacific Database (CSMAR), the Vantage Database, and the China Research Data Service Platform (CNRDS). The following steps are performed on the research sample: First, financial listed companies are excluded. Second, sample companies that were ST, PT, or delisted during the observation period are excluded. Third, samples with missing indicators of important variables are excluded. This study finally obtains 25,216 sample observations. Meanwhile, all continuous variables are shrink-tailed by 1% and 99% up and down to exclude the interference of outliers.

The results of descriptive statistics are shown in Table 1. The minimum value of corporate dualization and synergistic transformation (dgst) is 0.1980, and the standard deviation is 0.0943, which indicates that the degree of dualization and synergistic transformation of different listed companies varies to some extent. For green manufacturing (policy) as a dummy variable, the minimum value is 0, the maximum value is 1, and the mean value is 0.7214. For the control variables, the age of enterprises (age) is distributed in the range 0.6931–3.4965, the mean value is 2.2134, and the difference in the age of enterprises is small. Total gearing ratio (tor) has a mean value of 0.4233, indicating that, on average, about 42.33% of the assets in the sample of firms examined are financed through debt. The mean value of return on equity (roe) is −0.0088, implying that each unit of shareholders’ equity generates a net profit of −0.88%, and the capital invested is not utilized effectively. The mean value of equity concentration (eci) is about 52.1596, indicating that the top five outstanding shareholders of the company have a considerable influence over the company. The nature of property rights (soe) is a dummy variable, and its value ranges from 0 to 1, with a mean value of 0.0979. Regarding the mechanism variable, green technology innovation (gpatent) has an average value of 6.0247 and a standard deviation of 43.9492. The wide range of this distribution indicates significant disparities in green technology innovation among different firms. The mean value of public environmental concern (public) is 237.8679, implying that the public generally has high awareness and concern for environmental protection and sustainable development. The mean value of financing constraint level credit cost (sa) is −3.8330, which may imply that firms, on average, receive some kind of preference or subsidy when financing, which reduces their financing cost. The mean value of ESG level (hesg) is 4.0802, with a standard deviation of 1.0043. That is, differences exist among individuals in ESG investment of listed companies, with a large room for improvement in the overall view.

**Table 1.** Results of descriptive statistics of variables.

| Variables | Sample Size | Average Value | Standard Deviation | Minimum | Maximum |
|-----------|-------------|---------------|--------------------|---------|---------|
| dgst      | 25,216      | 0.3491        | 0.0943             | 0.1980  | 0.9038  |
| policy    | 25,216      | 0.7214        | 0.2587             | 0       | 1       |
| age       | 25,216      | 2.2134        | 0.7243             | 0.6931  | 3.4965  |
| tor       | 25,216      | 0.4233        | 0.1997             | 0.0080  | 0.9976  |

Table 1. Cont.

| Variables | Sample Size | Average Value | Standard Deviation | Minimum | Maximum   |
|-----------|-------------|---------------|--------------------|---------|-----------|
| roe       | 25,216      | −0.0088       | 1.9612             | −1.8655 | 0.6456    |
| eci       | 25,216      | 52.1596       | 15.2131            | 2.9786  | 99.2300   |
| soe       | 25,216      | 0.0979        | 0.2972             | 0       | 1         |
| gpatent   | 22,727      | 6.0247        | 43.9492            | 0       | 2117      |
| public    | 23,796      | 237.8679      | 233.2845           | 0       | 1273.9940 |
| sa        | 25,216      | −3.8330       | 0.2662             | −5.3579 | −2.0936   |
| hesg      | 25,216      | 4.0802        | 1.0043             | 1       | 8         |

## 5. Analysis of Empirical Results

### 5.1. Baseline Regression Analysis

Table 2 presents the regression results of model (1). Column (1) represents the univariate regression controlling for firm and year fixed effects. The coefficient of policy is significantly positive—i.e., the level of dual transformation is significantly increased when a firm obtains the “green factory” certification—which is in line with H1. Columns 2–6 show the regression results after gradually adding firm-level control variables, and the effect remains significant. When all control variables are included in the estimation results, the coefficient of the independent variable is 0.0207. That is, with every unit change in green manufacturing, the level of enterprise dual transformation will be increased by 2.07%, and green manufacturing has a significant driving effect on enterprise dual transformation. The regression results of other control variables show that the longer the listing period is, the higher the total gearing ratio (tor), return on equity (roe), and equity concentration (eci) are; hence, the higher the level of dual transformation is. By contrast, the enhancement effect of property rights nature on dual transformation is insignificant.

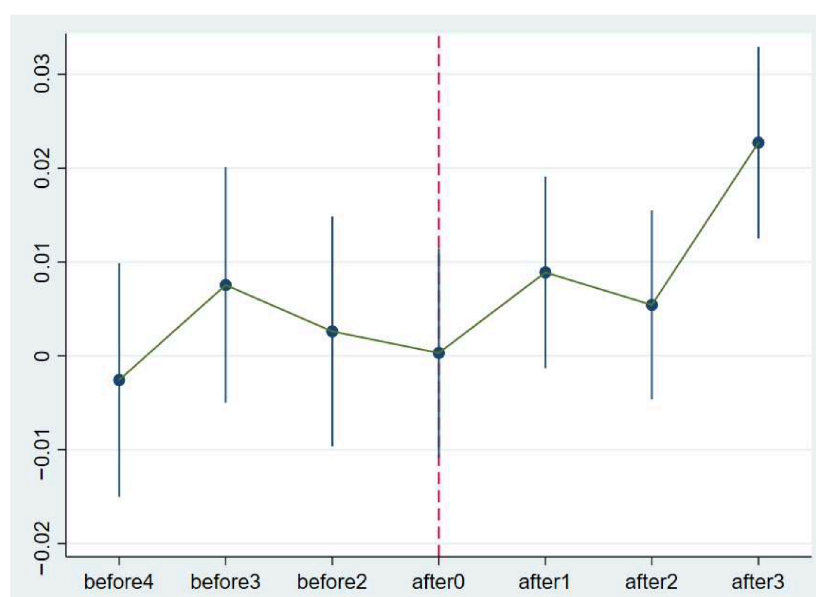
Table 2. Results of the baseline regression analysis.

| Variables           | (1)                      | (2)                      | (3)                      | (4)                      | (5)                     | (6)                     |
|---------------------|--------------------------|--------------------------|--------------------------|--------------------------|-------------------------|-------------------------|
|                     | dgst                     | dgst                     | dgst                     | dgst                     | dgst                    | dgst                    |
| policy              | 0.0216 ***<br>(4.26)     | 0.0213 ***<br>(4.21)     | 0.0213 ***<br>(4.22)     | 0.0207 ***<br>(4.08)     | 0.0208 ***<br>(4.10)    | 0.0207 ***<br>(4.09)    |
| lnage               |                          | 0.0305 ***<br>(6.90)     | 0.0290 ***<br>(6.32)     | 0.0289 ***<br>(6.28)     | 0.0386 ***<br>(8.05)    | 0.0387 ***<br>(8.06)    |
| Intor               |                          |                          | 0.0033<br>(1.25)         | 0.0053 *<br>(1.95)       | 0.0064 **<br>(2.36)     | 0.0064 **<br>(2.36)     |
| lnroe               |                          |                          |                          | 0.0134 ***<br>(3.50)     | 0.0113 ***<br>(2.96)    | 0.0113 ***<br>(2.96)    |
| lneci               |                          |                          |                          |                          | 0.0407 ***<br>(7.11)    | 0.0402 ***<br>(7.00)    |
| soe                 |                          |                          |                          |                          |                         | 0.0034<br>(0.97)        |
| _cons               | −1.3502 ***<br>(−456.06) | −1.3602 ***<br>(−412.84) | −1.3558 ***<br>(−282.48) | −1.3545 ***<br>(−278.99) | −1.5198 ***<br>(−64.00) | −1.5182 ***<br>(−63.79) |
| individual fixation | Yes                      | Yes                      | Yes                      | Yes                      | Yes                     | Yes                     |
| fixed time          | Yes                      | Yes                      | Yes                      | Yes                      | Yes                     | Yes                     |
| N                   | 25,216                   | 25,216                   | 25,216                   | 24,933                   | 24,933                  | 24,933                  |
| R2                  | 0.573                    | 0.573                    | 0.573                    | 0.575                    | 0.576                   | 0.576                   |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

### 5.2. Parallel Trend Test

The parallel trend test is a prerequisite for the application of the DID model, and the results of DID can only be accurate if the parallel trend is satisfied. The parallel trend test requires the control group to maintain the same development trend before the policy is applied to ensure the application of the policy. For examining the dynamic treatment effect of the selected green factory demonstration construction projects over time, a parallel trend test is conducted (Figure 1). The obtained results show that the level of dual transformation of “green factories” is insignificantly different from that of enterprises that are not recognized as “green factories” in the first four periods. However, after the recognition as “green factory,” the level of dual transformation has been significantly improved. Thus, the above results validate the parallel trend hypothesis.



**Figure 1.** Parallel trend test results Note: The horizontal axis now reads “Time Relative to Policy Implementation” (with periods denoted as pre-4, pre-3, pre-2, pre-1, current, post-1, post-2, etc.), and the vertical axis now reads “Estimated Coefficient of Dual Transformation Level”.

### 5.3. Robustness and Endogeneity Discussion

To confirm the robustness of the regression outcomes, this study re-verifies the model by using different approaches.

#### 5.3.1. Propensity Score Matching (PSM)-DID Methodology

To eliminate the endogeneity problem caused by selection bias, this study refers to the paper of Yang and Rui (2020) and selects the PSM-DID method to accurately assess the impact of green manufacturing on dualization and synergistic transformation [31]. In the PSM-DID analysis, using diverse samples and weighting methods can lead to different meanings. Among them are the use of a weighted nonempty sample that includes all observations without any form of filtering or weighting of the sample; the use of a sample that satisfies the common support assumption, which allows for overlapping regions in the distribution of propensity scores for the treatment and control groups, improving the confidence of the match; and the use of a frequency weighted regression model to adjust the weights of certain observations in the sample to reflect their representativeness in the overall population. In Table 3, column (1) shows the results of the mixed OLS regression, column (2) presents the outcomes of the fixed-effect regression model, column (3) demonstrates the results of the regression employing the PSM-DID weights for non-null

samples, column (4) exhibits the results of the regression using the samples that meet the assumptions of coexistence, and column (5) reveals the results of the application of the frequency weighted regression model. The coefficients of green manufacturing are all significantly positive, suggesting that green manufacturing markedly enhances the level of dualization and synergistic transformation of enterprises, which verifies H1.

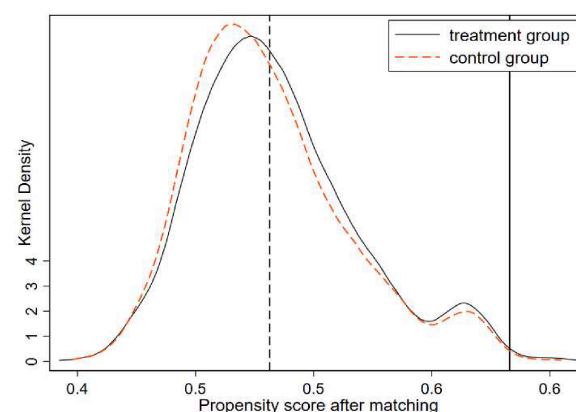
**Table 3.** Benchmark regression and cross-sectional PSM-DID results.

| Variables | (1)                    | (2)                  | (3)                  | (4)                  | (5)                  |
|-----------|------------------------|----------------------|----------------------|----------------------|----------------------|
| policy    | 0.0833 ***<br>(13.91)  | 0.0207 ***<br>(4.09) | 0.0224 ***<br>(3.74) | 0.0189 ***<br>(3.64) | 0.0232 ***<br>(5.53) |
| lnage     | 0.0307 ***<br>(7.08)   | 0.0387 ***<br>(8.06) | 0.0115 *<br>(1.94)   | 0.0139 ***<br>(2.71) | 0.0068<br>(1.62)     |
| Intor     | −0.0009<br>(−0.32)     | 0.0064 **<br>(2.36)  | 0.0037<br>(1.13)     | 0.0056 **<br>(1.98)  | 0.0029<br>(1.19)     |
| lnroe     | −0.0203 ***<br>(−2.84) | 0.0113 ***<br>(2.96) | 0.0106 **<br>(2.35)  | 0.0122 ***<br>(2.98) | 0.0085 **<br>(2.47)  |
| lneci     | −0.0463 ***<br>(−8.99) | 0.0402 ***<br>(6.99) | 0.0277 ***<br>(3.85) | 0.0297 ***<br>(4.76) | 0.0195 ***<br>(3.78) |
| soe       | −0.0446 ***<br>(−8.34) | 0.0034<br>(0.97)     | 0.0041<br>(0.98)     | 0.0050<br>(1.37)     | 0.0051 *<br>(1.67)   |
| N         | 24,933                 | 24,933               | 16,689               | 20,924               | 28,424               |
| R2        | 0.019                  | 0.576                | 0.565                | 0.563                | 0.565                |

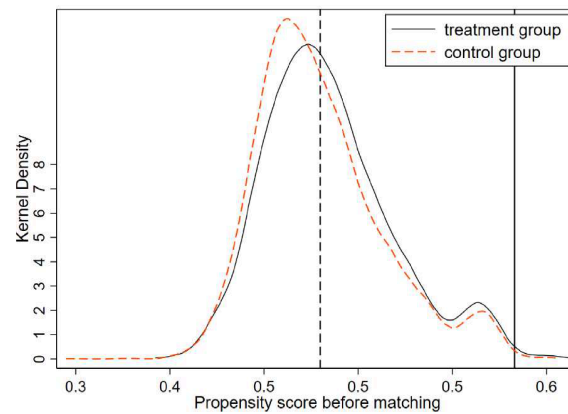
Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

### 5.3.2. Placebo Test

The premise of using the DID model is that the policy has its origins in the enterprise, but in fact, whether the enterprise applies blockchain technology is not randomly selected; it is the result of the enterprise's own choice, which will lead to the endogeneity of the constructed multitemporal DID model with sample selection bias, and the multitemporal DID model cannot be applied. The PSM method put forward by Rosenbaum and Rubin (1983) can handle the problem more effectively [48]. Although matching reduces the bias of the characteristics of treatment and control groups, the PSM model is still invalid if the propensity of the scores of treatment and control groups differs greatly and the quality of matching is poor. Therefore, the common tendency test is essential, which aims to confirm that the tendency scores have sufficient overlapping regions between treatment and control groups. The kernel density plots before and after matching are shown in Figures 2 and 3, respectively. After matching, the treatment and control groups are much closer, and the overlap region is significantly larger. This result indicates that the matching is of excellent effectiveness, and the PSM estimation is reliable.

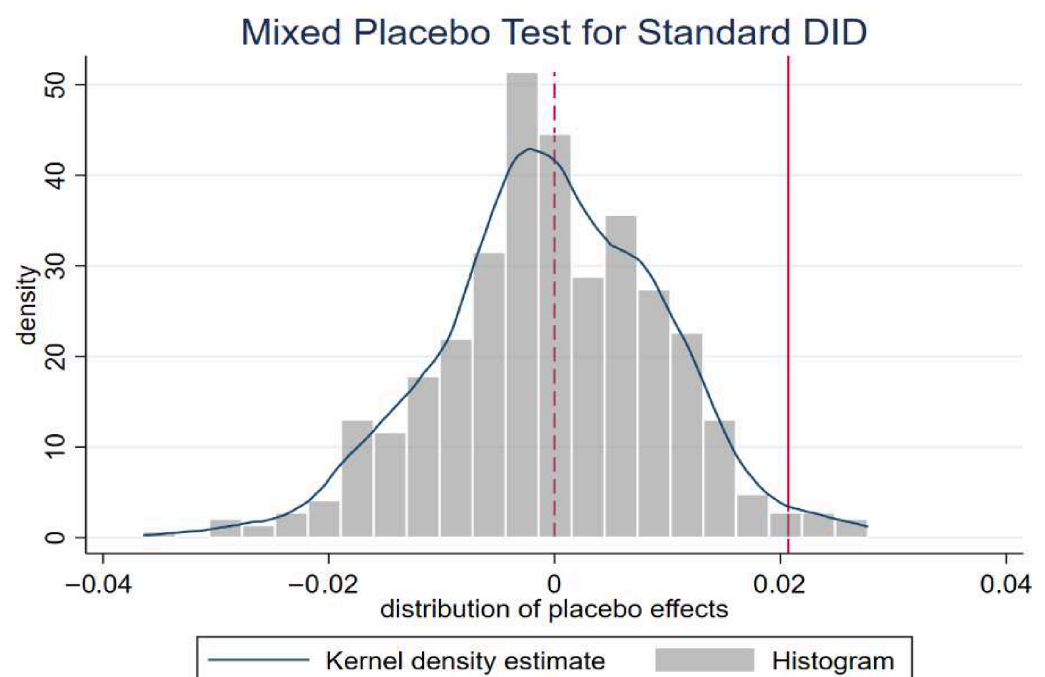


**Figure 2.** PSM-DID results before matching.



**Figure 3.** Result after PSM-DID matching.

A common concern with the double-difference (DID) method is that some unobserved, time-varying prefecture-specific factors may interfere with the estimation results. While fixed-effect models are able to control for unobservable firm-specific qualities that do not change over time, this approach may not be able to help with variables that change over time. The placebo test, on the contrary, can help us assess whether a model is affected by variables that are not included in the analysis. The placebo test is widely used [49], in which the idea is to find an error variable in place of the interaction term that theoretically would not have an effect on the results, typically by randomly assigning treatment and control groups and the time of the event and re-estimating the model. If the estimated coefficient on the interaction term is insignificant, it is indirect evidence that the baseline estimates remain valid even in the presence of unobservables. Specifically, we generate an incorrectly estimated coefficient by randomly generating a list of treatment groups in all samples and an event time in all years  $\beta_{\text{random}}$  and then repeat this process 500 times to produce 500  $\beta_{\text{random}}$ . The results are shown in Figure 4, which demonstrate that  $\beta_{\text{random}}$  values are all distributed around 0 and follow a normal distribution, indicating that the placebo test is passed.



**Figure 4.** Placebo test results.

### 5.3.3. Substitution of Explanatory Variables

The coupling coordination degree model is a research tool used to assess the coordination between multiple subsystems. It was initially used in the field of physics and later introduced into social sciences, where it has been widely used, especially in urban economics and regional development studies. The model analyzes the interaction and coordination status between different subsystems through quantitative methods to evaluate the overall degree of balanced development of a complex system. For model (1), this study adopts the robustness test by replacing the explanatory variables with the recalculated dual transformation of enterprises using the coupling coordination degree model, and the results are shown in columns (1) and (2) of Table 4. The effect of green manufacturing on dual transformation is still significantly positive, indicating that the regression results of H1 are robust.

**Table 4.** Robustness test results.

| Variables           | (1)                                   | (2)                     | (3)                        | (4)                     |
|---------------------|---------------------------------------|-------------------------|----------------------------|-------------------------|
|                     | Substitution of Explanatory Variables |                         | Deletion of Municipalities |                         |
| policy              | 0.0630 ***<br>(11.53)                 | 0.0104 **<br>(1.98)     | 0.1253 ***<br>(32.59)      | 0.0061 *<br>(1.75)      |
| lnage               | 0.2443 ***<br>(59.64)                 | 0.0491 ***<br>(9.89)    | 0.3187 ***<br>(58.83)      | 0.0328 ***<br>(5.90)    |
| lntr                | −0.0039<br>(−1.27)                    | 0.0021<br>(0.76)        | −0.0004<br>(−0.11)         | 0.0061 *<br>(1.94)      |
| lnroe               | −0.0021<br>(−0.48)                    | 0.0015<br>(0.39)        | 0.0077<br>(1.36)           | 0.0114 **<br>(2.45)     |
| lneci               | −0.0091<br>(−1.42)                    | 0.0201 ***<br>(3.37)    | −0.0052<br>(−0.66)         | 0.0386 ***<br>(5.97)    |
| soe                 | 0.0053<br>(1.34)                      | 0.0015<br>(0.41)        | 0.0091 *<br>(1.80)         | 0.0038<br>(0.92)        |
| _cons               | −1.3853 ***<br>(−52.01)               | −1.5208 ***<br>(−61.72) | −1.3757 ***<br>(−42.38)    | −1.5151 ***<br>(−56.73) |
| individual fixation | Yes                                   | Yes                     | Yes                        | Yes                     |
| fixed time          | No                                    | Yes                     | No                         | Yes                     |
| N                   | 24,933                                | 24,933                  | 18,799                     | 18,799                  |
| R2                  | 0.209                                 | 0.334                   | 0.362                      | 0.575                   |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

### 5.3.4. Deletion of Some Samples

In consideration of the level of economic development of the four municipalities directly under the central government, Beijing, Tianjin, Chongqing, and Shanghai, the advantages of policies and resources may lead to the investment and effectiveness of green manufacturing and dual transformation of these regions being different from those of other regions. Their data may constitute statistical outliers, which may interfere with the overall analysis of the data and affect the robustness of the results. Therefore, these samples are excluded to regress model (1), as shown in columns (3) and (4) of Table 4. Green manufacturing still has a notable reinforcing impact on dual transformation, which verifies H1.

### 5.4. Heterogeneity Analysis

In general, green manufacturing can effectively motivate enterprises to improve the level of dual transformation, but differences exist in the effect of green manufacturing on the enhancement of dual transformation with diverse attributes and characteristics. Thus, what types of enterprises are significantly enhanced by green manufacturing? The identification

of such heterogeneity factors is crucial for enhancing the “green factory” recognition policy and boosting the efficiency of policy implementation. For this purpose, this study examines the heterogeneous impacts of green manufacturing on the dual transformation of enterprises from four dimensions: regional heterogeneity, life cycle heterogeneity, pollution degree, and executive heterogeneity.

#### 5.4.1. Regional Heterogeneity

The different economic foundations and resource endowments in various regions of China are likely to lead to underinvestment in capital, human capital, and technological innovation by enterprises in some regions, which ultimately leads to differences in the impact of green manufacturing on the dual transformation of enterprises. In this regard, this study divides China into east, center, and west for group testing. The results in Table 5 show that the enhancement effect of green manufacturing on the collaborative dualization transformation of enterprises is significantly positive in the eastern and western regions, and the coefficient in the western region is greater than that in the eastern region. This finding may be due to the fact that in terms of investment and policy support for green manufacturing, the western region enjoys the government’s policy favoritism and financial support and receives more resources and infrastructure construction. Meanwhile, the industrial structure in the western region might be at the stage of transformation and upgrading, and the enterprises’ investment and transformation needs in green manufacturing are more urgent; hence, the effect of green manufacturing is more obvious. Enterprises in the eastern region may already have a high foundation in green manufacturing and digitalization, with relatively little room for further improvement. By contrast, implementing green manufacturing in the central region cannot effectively enhance dual transformation. The market environment in the central region may not be sufficiently matched with the promotion and application of green manufacturing, resulting in enterprises being limited in implementing green manufacturing.

**Table 5.** Regression results for regional heterogeneity.

| Variables           | (1)                     | (2)                     | (3)                     |
|---------------------|-------------------------|-------------------------|-------------------------|
|                     | Eastern Region          | Central Region          | Western Region          |
| policy              | 0.0220 ***<br>(3.40)    | 0.0136<br>(1.45)        | 0.0313 **<br>(2.00)     |
| lnage               | 0.0317 ***<br>(5.59)    | 0.0437 ***<br>(3.75)    | 0.0767 ***<br>(4.61)    |
| Intor               | 0.0061 *<br>(1.87)      | 0.0020<br>(0.30)        | 0.0125<br>(1.41)        |
| lnroe               | 0.0115 **<br>(2.51)     | 0.0200 **<br>(2.36)     | 0.0016<br>(0.12)        |
| lneci               | 0.0274 ***<br>(3.90)    | 0.0307 **<br>(2.44)     | 0.0932 ***<br>(5.04)    |
| soe                 | −0.0002<br>(−0.05)      | 0.0074<br>(1.08)        | 0.0108<br>(1.28)        |
| _cons               | −1.4518 ***<br>(−49.71) | −1.5168 ***<br>(−29.40) | −1.7807 ***<br>(−23.40) |
| individual fixation | Yes                     | Yes                     | Yes                     |
| fixed time          | Yes                     | Yes                     | Yes                     |
| N                   | 17,736                  | 4470                    | 2346                    |
| R2                  | 0.564                   | 0.615                   | 0.582                   |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

#### 5.4.2. Differences Across Enterprise Life Cycle

Given that enterprises entering the capital market must comply with the relevant listing requirements, they should meet certain conditions in terms of scale of operation and earnings. As a result, going public signifies that the enterprise has passed the initial start-up period. Therefore, this study refers to the study of Anthony et al. (1992) [50], which adopts sales revenue growth rate, retained earnings rate, capital expenditure rate, and enterprise age to divide the life cycle of the enterprise. According to the fact that the listed enterprises in China have already passed the initial period of start-up and in consideration of the differences between the industries, the life cycle of the enterprise is divided into three phases: the growth, maturity, and decline periods. Specifically, the  $\frac{1}{4}$  segment with the highest score is the enterprises in the growth period, the  $\frac{1}{4}$  segment with the lowest score is the enterprises in the decline period, and the middle segment is the enterprises in the maturity period. For exploring the heterogeneity of the performance of enterprise green manufacturing on dual transformation in different life cycle stages of enterprises, regression on the grouping of enterprises in the three stages is obtained in Table 6. The results reveal that the enhancing impact of enterprise green manufacturing on dual transformation is not notable in the growth stage. On the contrary, it is significantly positive in the decline and maturity stages, and the enhancement effect of green manufacturing is greater in the decline stage than that in the maturity stage. The possible reasons for this finding are as follows: Growth-stage firms are focused on expansion and market share growth and therefore may either invest less in or pay less attention to green manufacturing. Firms in the maturity stage are under pressure to compete in the market and maintain their market position and may use green manufacturing as a means to enhance their brand image and attract consumers. By contrast, firms in decline may seek to restore growth or find new market opportunities through green manufacturing. Therefore, significant differences in the response to and effectiveness of green manufacturing may occur at different stages of an enterprise's life cycle, requiring the enterprise to formulate an appropriate green development strategy based on its own characteristics and market environment.

**Table 6.** Business life cycle regression results.

| Variables           | (1)                     | (2)                     | (3)                      |
|---------------------|-------------------------|-------------------------|--------------------------|
|                     | Formative Years         | Maturity                | Recession (In Economics) |
| policy              | 0.0189<br>(1.21)        | 0.0236 ***<br>(2.89)    | 0.0245 ***<br>(2.67)     |
| lnage               | 0.0475 ***<br>(3.52)    | 0.0316 ***<br>(3.91)    | 0.0323 ***<br>(3.29)     |
| Intor               | 0.0032<br>(0.40)        | 0.0142 ***<br>(2.99)    | 0.0057<br>(1.16)         |
| lnroe               | 0.0003<br>(0.03)        | 0.0132 *<br>(1.91)      | 0.0163 **<br>(2.48)      |
| lneci               | 0.0097<br>(0.53)        | 0.0384 ***<br>(3.88)    | 0.0183 *<br>(1.79)       |
| soe                 | −0.0116<br>(−0.96)      | 0.0057<br>(0.96)        | 0.0061<br>(1.11)         |
| _cons               | −1.3826 ***<br>(−17.80) | −1.5006 ***<br>(−36.61) | −1.4371 ***<br>(−33.94)  |
| individual fixation | Yes                     | Yes                     | Yes                      |
| fixed time          | Yes                     | Yes                     | Yes                      |
| N                   | 4388                    | 10,875                  | 9180                     |
| R2                  | 0.528                   | 0.561                   | 0.594                    |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

### 5.4.3. Business Attributes and Executive Backgrounds

In addition to the differences in geographic location and the life cycle of firms, the strengthening effect of green manufacturing on the dual transformation of firms may be related to the pollution degree of the industry and whether the executives have an overseas background. Columns (1) and (2) of Table 7 show the effects of green manufacturing on the dual transformation of enterprises with different pollution levels. The coefficients are both significantly positive, indicating that the green manufacturing of heavily and nonheavily polluting enterprises has an enhancement effect on the dual transformation of enterprises. However, the coefficients of green manufacturing of heavily polluting enterprises are larger than those of nonheavily polluting enterprises. Heavily polluting enterprises may have a greater impact on the environment due to their production process and face relatively greater external environmental regulatory pressure. Consequently, there is more room for improvement in green manufacturing, the effect of the implementation of green measures is more pronounced, and the enterprise's green manufacturing is more effective in enhancing the level of dual transformation. Columns (3) and (4) of Table 7 provide the heterogeneous impacts of firms' green manufacturing on dual transformation with and without executives' overseas background. Corporate green manufacturing has no significant effect on dual transformation when executives have an overseas background, and the coefficient of corporate green manufacturing is positive at 1% level of significance when executives do not have an overseas background. When executives have an overseas background, firms have internalized the concept of green manufacturing given their international perspective and experience; thus, the enhancement effect of green manufacturing on dual transformation is no longer significant. Executives without an overseas background, on the contrary, rely more on green manufacturing as a driving force for innovation and transformation and respond more positively to policies and regulations encouraging green manufacturing; thus, the effect of green manufacturing on enhancing their dual transformation is more significant.

**Table 7.** Regression results of firm affiliation type and executive heterogeneity.

| Variables           | (1)                     | (2)                     | (3)                                 | (4)                                    |
|---------------------|-------------------------|-------------------------|-------------------------------------|----------------------------------------|
|                     | Heavy Pollution         | Nonheavy Pollution      | Executives with Overseas Background | Executives Have No Overseas Background |
| policy              | 0.0370 ***<br>(5.04)    | 0.0148 **<br>(2.19)     | −0.0057<br>(−0.55)                  | 0.0326 ***<br>(5.61)                   |
| lnage               | 0.0291 ***<br>(3.33)    | 0.0446 ***<br>(7.77)    | 0.0309 ***<br>(3.82)                | 0.0102 *<br>(1.65)                     |
| Intor               | −0.0124 ***<br>(−2.79)  | 0.0158 ***<br>(4.59)    | 0.0135 ***<br>(2.64)                | 0.0033<br>(1.02)                       |
| lnroe               | 0.0045<br>(0.68)        | 0.0179 ***<br>(3.75)    | 0.0123 *<br>(1.66)                  | 0.0106 **<br>(2.42)                    |
| lneci               | 0.0577 ***<br>(5.77)    | 0.0327 ***<br>(4.58)    | 0.0506 ***<br>(4.13)                | 0.0209 ***<br>(3.20)                   |
| soe                 | −0.0018<br>(−0.31)      | 0.0053<br>(1.20)        | 0.0151 **<br>(2.01)                 | 0.0025<br>(0.66)                       |
| _cons               | −1.6833 ***<br>(−40.32) | −1.4424 ***<br>(−48.76) | −1.5337 ***<br>(−30.00)             | −1.4407 ***<br>(−52.97)                |
| individual fixation | Yes                     | Yes                     | Yes                                 | Yes                                    |
| fixed time          | Yes                     | Yes                     | Yes                                 | Yes                                    |
| N                   | 7589                    | 17,336                  | 8446                                | 16,487                                 |
| R2                  | 0.595                   | 0.566                   | 0.519                               | 0.591                                  |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

### 5.5. Further Impact Mechanism Analysis

The above empirical evidence suggests that green manufacturing of enterprises strongly promotes the significant improvement of the level of dual transformation [51,52]. However, the specific mechanism underlying this effect remains unclear. On this basis, we further conduct a mechanism analysis, expecting to clarify the manner in which green manufacturing functions in the process of enterprises' dualization and synergistic transformation. Column (1) of Table 8 shows the results of the baseline regression, which builds a reference framework for the subsequent analysis. Column (2) reflects the role of green manufacturing in firms' green technology innovation, and the results show that the coefficient of green manufacturing is positive at the 1% significance level. For every unit increase in green manufacturing inputs, the level of firms' green technology innovation will increase by 0.0922 units. This finding suggests that green manufacturing can enhance the level of dual transformation by driving enterprises to invest R&D resources and promote green technology innovation, verifying H2.

**Table 8.** Results of mechanism of action tests.

| Variables              | (1)<br>dgst             | (2)<br>gpatent         | (3)<br>Public           | (4)<br>sa               | (5)<br>hesg            |
|------------------------|-------------------------|------------------------|-------------------------|-------------------------|------------------------|
| policy                 | 0.0207 ***<br>(4.09)    | 0.0922 ***<br>(3.11)   | 21.8011 ***<br>(4.86)   | −0.0020 ***<br>(−3.88)  | 0.0614 ***<br>(6.85)   |
| lnage                  | 0.0387 ***<br>(8.06)    | −0.0659 **<br>(−2.27)  | −14.0320 ***<br>(−3.28) | 0.0189 ***<br>(38.64)   | −0.0617 ***<br>(−7.26) |
| Intor                  | 0.0064 **<br>(2.36)     | 0.0022<br>(0.14)       | 13.6813 ***<br>(5.68)   | 0.0037 ***<br>(13.23)   | −0.0428 ***<br>(−8.88) |
| lnroe                  | 0.0113 ***<br>(2.96)    | 0.0004<br>(0.02)       | 11.0264 ***<br>(3.19)   | 0.0008 **<br>(2.11)     | 0.0132 *<br>(1.94)     |
| lneci                  | 0.0402 ***<br>(7.00)    | −0.1159 ***<br>(−3.24) | 11.8781 **<br>(2.34)    | −0.0094 ***<br>(−16.01) | 0.0406 ***<br>(3.99)   |
| soe                    | 0.0034<br>(0.97)        | −0.0048<br>(−0.22)     | 2.6351<br>(0.86)        | 0.0013 ***<br>(3.55)    | −0.0132 **<br>(−2.14)  |
| _cons                  | −1.5182 ***<br>(−63.79) | 1.0365 ***<br>(7.02)   | 42.8764 **<br>(2.04)    | 1.3155 ***<br>(542.68)  | 1.2365 ***<br>(29.33)  |
| individual<br>fixation | Yes                     | Yes                    | Yes                     | Yes                     | Yes                    |
| fixed time             | Yes                     | Yes                    | Yes                     | Yes                     | Yes                    |
| N                      | 24,933                  | 22,480                 | 23,529                  | 24,933                  | 24,933                 |
| R2                     | 0.576                   | 0.028                  | 0.420                   | 0.874                   | 0.030                  |

Note: For t statistics in parentheses, \*  $p < 0.1$ , \*\*  $p < 0.05$ , and \*\*\*  $p < 0.01$ .

Public scrutiny strongly promotes dual transformation. The results in column (3) of Table 8 show the significant positive effect of green manufacturing on public environmental concern. That is, as companies continue their efforts in green manufacturing, their brand image and trust in the minds of consumers and investors are significantly enhanced, which in turn increases the public's awareness of and concern for corporate environmental responsibility. This brand effect and the establishment of public trust are of inestimable value to the long-term sustainable development of enterprises. H3 is verified. Column (4) explores the effect of green manufacturing on the degree of corporate financing constraints, and the coefficient is notably negative. This finding may imply that the government's encouragement and support for green manufacturing, such as tax incentives, subsidies, and financial support policies, effectively reduce the credit cost of enterprises and alleviate their financing constraints. This merit provides a relaxed financing environment for enterprises,

which in turn contributes to the advancement of their green manufacturing and dual-chemistry synergy transformation projects, validating H4.

Lastly, column (5) analyzes the effect of green manufacturing on firms' ESG level, and, again, the results are significantly positive. This finding suggests that green manufacturing is not only a production practice but also a catalyst for firms to take proactive measures in terms of ESG. Through green manufacturing, companies can effectively identify and manage environment-related risks and improve their ESG, thus establishing a responsible corporate image in the market and contributing to the smooth implementation of their dual-transformation process. In summary, green manufacturing positively affects the dual transformation of enterprises through multifaceted mechanisms. These findings not only enrich our understanding of the mechanism of green manufacturing's role but also provide useful guidance for relevant policy formulation and enterprise strategy implementation, validating H5.

The four identified mechanisms are not mutually exclusive; rather, they exhibit both parallel and progressive characteristics. On one hand, green innovation and ESG improvement represent direct firm-level channels that operate simultaneously in response to the certification signal. On the other hand, a progressive logic also exists: green factory certification first stimulates green technological innovation, which in turn enhances ESG performance and attracts public environmental concern. Meanwhile, the certification signals credibility to financial institutions, directly easing financing constraints, which subsequently provides the necessary capital for further green innovation and ESG investments. This suggests that the four mechanisms function as an interconnected system rather than isolated pathways.

## 6. Conclusions and Implications

### 6.1. Conclusions of the Study

In the context of high-quality economic development, the synergistic transformation of digitalization and greening is an inevitable choice for enterprises seeking to achieve high-quality growth. On the basis of data from A-share listed companies in China from 2012 to 2022, this study takes the creation of green factories under a green manufacturing system as the core explanatory variable and explores its impact and mechanisms on dual transformation from a microperspective. The research results indicate that green manufacturing significantly enhances the level of dual transformation in enterprises. The mechanism analysis reveals that green manufacturing promotes dual transformation primarily by improving green technology innovation, increasing public environmental awareness, enhancing ESG, and alleviating financing constraints. The heterogeneity analysis shows that green manufacturing in eastern and western regions significantly drives the dual transformation of enterprises. The impact of green manufacturing is notably significant for enterprises in the mature and declining stages, whereas its effect on enterprises in the growth stage is less pronounced. Compared with nonheavily polluting enterprises, heavily polluting enterprises experience a more pronounced effect of green manufacturing. For enterprises with executives having an overseas background, the enhancement of dual transformation is insignificant; by contrast, for enterprises without executives with overseas backgrounds, the effect is significant. Therefore, policymakers should strengthen the synergy of recognition policies and other policy tools on the basis of the characteristics of enterprises to improve incentive effectiveness and accelerate the synergistic transformation of digitalization and greening.

### 6.2. Policy Recommendations

From the above findings, the following practice and policy implications can be drawn.

- (1) Enterprises need to recognize the significance of green manufacturing. The “green factory” recognition should be promoted as a basis for the realization of the complementary efficiency of voluntary environmental policy and other policy tools. Continuous tracking review and recognition of the dynamic adjustment of the list should also be strengthened. This study further suggests to strictly examine whether the declared enterprises meet the conditions for “green factory” recognition, prevent false declarations, penalize enterprises with such behavior, and reduce the degree of resource mismatch.
- (2) In the practice of enterprise digitalization and green transformation, enterprises should be fully aware of their own life cycle stage, purposefully and actively guide green manufacturing in a reasonable direction to empower dual transformation, and strongly provide resource support for it. Specifically, in the growth stage, enterprises should be able to set up green manufacturing pilot projects or innovation laboratories and try small-scale green manufacturing practices to explore the feasibility of dual transformation at low cost and risk. In the maturity stage, enterprises should make in-depth applications in green manufacturing to enhance the level of green manufacturing. For enterprises in the decline stage, they can be provided with targeted green manufacturing support policies, such as green transformation funds and preferential loans, to help them gain new growth points through green transformation.
- (3) Enterprise green manufacturing empowers enterprises to perform dual transformation in various regions with significantly different effects. In the eastern region, where development is more mature, this study recommends further promotion of innovation and incentivize enterprises to invest in advanced green manufacturing technologies and digital solutions. The western region should continue to invest in the construction of green manufacturing infrastructure and the cultivation of technical talents in the field of digitization to enhance the professionalism of enterprises in green manufacturing and dual transformation. Cooperation and resource sharing between enterprises in the central region and those in the eastern and western parts of the country should be promoted. Enterprises in the central region should be helped to learn from the cutting-edge technologies and management experience in the east, as well as the green manufacturing practices in the west.
- (4) The government needs to formulate matching policies for enterprises with different levels of pollution and lead them to scientifically enhance the level of “dual transformation.” Specifically, the government should give a grace period for heavily polluting enterprises and allow highly polluting enterprises to gradually realize the green empowerment of digitalization. It should also encourage enterprises whose executives have overseas backgrounds to participate in international seminars and training sessions on green manufacturing and digital transformation to enhance their knowledge of cutting-edge global green technologies and management models. This participation will help improve their understanding of green manufacturing, which will facilitate dual transformation. Enterprises whose executives do not have an overseas background are encouraged to collaborate with enterprises whose executives have an overseas background or green technology enterprises to share their experience and technology. Such collaboration can help them learn and implement advanced green manufacturing and digital transformation strategies quickly.
- (5) Enterprises should be encouraged to use government subsidies and science, technology, and innovation funds to increase their R&D investment in green technologies. They can be incentivized to actively explore and apply green technologies by setting up incentive mechanisms for green technology innovation. Strengthening publicity and education on environmental protection awareness and increasing public attention

to green actions by enterprises are recommended. Enterprises can also increase their interaction with the public through environmental information disclosure and transparency reports. To promote the establishment of a sound ESG structure and enhance corporate performance in ESG, enterprises should set clear ESG objectives and reflect them in their operations. Meanwhile, improving green financial policies and lowering the cost of financing for enterprises in green projects will effectively help enterprises in dual transformation. Financial institutions can be encouraged to provide favorable loan terms for green projects and set up green investment funds. Key enterprises in pilot cities must be given the opportunity to conduct the integrated development of digitization and greening with comprehensive financial and tax policies. Supporting pilot cities in forming a series of solutions through tax incentives, tax returns, or bonus funds, strengthening demonstration and replication, guiding and promoting the majority of small- and medium-sized enterprises in comprehensively upgrading the level of digitization and greening, and fostering the synergistic transformation of digitization and greening are further suggested.

### 6.3. Shortcomings and Prospects

This study has some constraints, implying future research opportunities. Specifically, current research focuses on the impact of external environmental factors on dual transformation. Intrinsic motivations and drivers also play a key role in the process of dualization and synergistic transformation of enterprises. Research has shown that the decision to transform a firm is not swayed by external incentives (e.g., policy support and market pressures) alone, but internal factors, including the innovative potential of employees, the adaptability of the organization, and the active promotion of management, are equally decisive [53–55]. These internal factors are critical to the success of a firm's transformation toward dualization and synergy, and they shape the firm's ability and strategy to cope with change, thus acting as a facilitator and enabler on the path of transformation. By optimizing these internal conditions, firms are able to respond effectively to external challenges and achieve transformation goals.

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