

Digital Technology, Green Fiscal and Tax Policies, and the Green Transformation of Traditional Manufacturing

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Abstract

Based on Chinese provincial panel data from 2011 to 2022, this paper explores the effects and mechanisms of digital technology and green fiscal and tax policies on the green transformation of traditional manufacturing. The research shows that digital technology has a significant enabling effect on the green transformation of traditional manufacturing. As regulatory instruments, green fiscal and tax policies significantly strengthen this enabling effect through the "compensation effect" and "cost effect" mechanisms respectively. However, the policy nesting of the two creates institutional friction, resulting in partial efficiency loss. Heterogeneity analysis indicates that the enabling effect of digital technology exhibits structural differences across different strategic regions and policy contexts. Extended analysis reveals that the enabling process of digital technology has "network effects" and threshold characteristics, with technology lock-in occurring at high quantiles, and the marginal effect of green fiscal policy showing a diminishing trend. Accordingly, this paper proposes building a full-chain digital empowerment foundation, implementing quantile-based governance of green fiscal and tax policies, promoting gradient regional ecological penetration, and applying targeted policies to break through transformation bottlenecks.

Keywords: Digital technology, Traditional manufacturing, Green transformation, Green fiscal policy, Green taxation

1. Introduction

The Third Plenary Session of the 20th Central Committee of the Communist Party of China clearly stated the need to "promote the high-end, intelligent, and green development of manufacturing." As the "ballast stone" of the national economy, manufacturing has achieved remarkable results in scale expansion and system improvement in recent years, but still has obvious shortcomings in factor input structure, product service quality, and innovation R&D capabilities. Especially under the traditional development model, manufacturing has long faced the dual dilemma of "high consumption" and "low efficiency," leading to continuously

intensifying resource and environmental pressures. Against this backdrop, the application of digital technology, particularly the deep penetration of digital technology in traditional manufacturing, plays a significant leading role in green transformation and is also an important means of achieving harmonious coexistence between humans and nature (Cao, et al., 2024). However, traditional manufacturing still faces two major challenges in the process of digital technology enabling green transformation: high technology iteration costs and the difficulty of effectively internalizing environmental negative externalities. This essentially reflects the failure of market mechanisms in the allocation of green resources. Relying solely on market forces is insufficient to spontaneously drive the green transformation process, and there is an urgent need to build incentive-compatible mechanisms through policy intervention to correct the structural deviation between corporate micro-decisions and social green development goals. Therefore, in the wave of upgrading from traditional "manufacturing" to "smart manufacturing," deeply exploring the cost adjustment, risk guarantee, and behavioral guidance roles of green fiscal and tax policies in the digital technology enabling process is not only a necessary measure to comply with the development of the digital economy but also a strategic choice to solve the green transformation dilemma of traditional manufacturing and achieve sustainable development.

Existing research has systematically revealed the enabling effects of digital technology on green transformation from three levels: regional, industrial, and enterprise. At the regional level, digital technology significantly improves cross-regional environmental collaborative governance capacity by building intelligent environmental monitoring networks and improving carbon emission accounting systems. At the industrial level, industrial digitalization and digital industrialization can empower the synergistic development of digitalization and greenization (hereinafter referred to as "digital-green") through cluster advantages and scale effects (Gu, et al., 2025), playing a strong role in promoting green economic efficiency. Digital platforms precisely match green supply and demand by optimizing green supply chains and market information transmission mechanisms, driving collaborative low-carbon transformation across the upstream and downstream of the industrial chain. At the enterprise level, the Internet of Things and artificial intelligence technologies not only improve production energy efficiency but also continuously improve superficial and strategic pollution control methods through digital R&D tools, promote low-carbon technology innovation, and effectively improve enterprise energy conservation and emission reduction efficiency. Furthermore, digital marketing strategies further guide green consumption choices, providing cash flow guarantees for enterprise clean production (Gao, et al., 2025). However, technological empowerment has natural limitations. The mismatch between transformation costs and benefit cycles can easily trap enterprises in a decision-making dilemma between digitalization and greenization investment. Coupled with the neutral characteristics of digital technology itself, its environmental benefits are highly dependent on institutional design, triggering the "Jevons Paradox" of resource consumption. Therefore, relying solely on technological empowerment is insufficient to achieve green transformation goals, and there is an urgent need to build an effective "technology-institution" collaborative governance system.

As a key institutional tool for correcting market failures, green fiscal and tax policies systematically advance the green transformation process through an "incentive-constraint" dual-wheel drive mechanism. On the one hand, green fiscal subsidy policies designed based on the principle of incentive compatibility—such as additional deductions for green technology R&D and investment credits for low-carbon equipment—can significantly reduce enterprise innovation costs and effectively alleviate the positive externality of green technology R&D. Empirical research shows that such policy tools not only produce significant carbon emission reduction effects but also demonstrate unique institutional advantages in coordinating economic growth and environmental protection. On the other hand, China has constructed a green tax system with environmental protection tax as the core, resource tax and farmland occupation tax as key supports, and the coordinated cooperation of multiple taxes including consumption tax and vehicle and vessel tax. This institutional design achieves the cost internalization of negative externality production by economic entities through the "polluter pays" principle, forcing enterprises to upgrade green technology (Molloy, 2019). At the same time, the gradual environmental tax system design can achieve a "double dividend" of emission reduction and innovation, providing an effective solution to break through the "carbon lock-in" dilemma. The promulgation and implementation of the "Opinions of the Central Committee of the Communist Party of China and the State Council on Accelerating the Comprehensive Green Transformation of Economic and Social Development" in August 2024 marked China's green fiscal and tax policies entering a new stage of institutionalized and systematic development. The document clearly requires "improving fiscal and tax policies for green transformation, and actively building a fiscal and tax policy system conducive to promoting green and low-carbon development and efficient resource utilization," indicating that future reforms will pay more attention to the combined use and synergistic effects of policy tools, reflecting China's transformation of green fiscal and tax policies from single policy tools to systematic institutional arrangements, and reflecting the deepening and innovation of environmental governance concepts.

In summary, existing research has produced rich results, but the following aspects still need deepening. First, the pertinence of research objects is insufficient; existing literature mostly focuses on the overall competitiveness improvement of manufacturing, lacking specialized discussion on traditional manufacturing—a strategically significant special area—and its theoretical and empirical research on green transformation needs expansion. Second, the mechanism discussion needs to be deepened; current research generally neglects the leverage regulation and synergistic interaction effects of regulatory tools such as green fiscal and tax policies, failing to precisely reveal the mechanism "black box" of technology application and policy tools. Third, the inherent attributes of fiscal and tax policies urgently need further exploration; existing literature generally recognizes the macro-control effectiveness of regulatory tools but fails to interpret the changing trends and mechanism characteristics of policy effects based on the level of digital technology application. Given this, this paper uses Chinese provincial panel data from 2011 to 2022 as a sample, incorporating digital technology, green fiscal and tax policies, and the green transformation of traditional manufacturing into a unified analytical framework, focusing on the direct impact of digital technology enabling the green transformation of traditional manufacturing and the leverage regulation role of green

fiscal and tax policies in the enabling process. That is, focusing on traditional manufacturing—a national strategic high ground—to enrich the theoretical framework of digital technology enabling green transformation and provide new empirical evidence for promoting high-quality development of traditional manufacturing. By incorporating green fiscal and tax policies into the analytical framework and systematically examining their regulation and policy combination effects in the digital technology enabling process, this paper provides reference and insight for deeply understanding the ecological value arising from the integration of "technology and policy." Based on differences in digital technology application levels, it reveals the inherent attributes of green fiscal and tax policies, aiming to enrich the theoretical research on industrial green transformation and provide a scientific basis for optimizing the design of fiscal and tax policy combinations.

2. Theoretical Analysis and Research Hypotheses

2.1 Digital Technology and the Green Transformation of Traditional Manufacturing

The green transformation of traditional manufacturing is a systematic change centered on resource conservation and environmental improvement, aimed at achieving synergistic improvement of economic efficiency and ecological benefits. However, this process generally faces three key challenges: insufficient traceability of environmental information, high complexity of multi-objective decision-making, and strong pollution response lag, which have severely constrained transformation effectiveness. Digital technology overcomes the core problems of "invisibility," "incalculability," and "uncontrollability" in the green transformation of traditional manufacturing through a three-dimensional synergistic empowerment mechanism of "perception-analysis-execution" (Ritter, 1991). Specifically, first, empowerment at the perception level lays the foundation for environmental transparency construction. To accurately track environmental information such as carbon footprints, digital technology, relying on the Internet of Things and blockchain, builds a digital monitoring network covering the entire lifecycle of design, production, logistics, and recycling, achieving full-chain visualization of resource consumption and environmental impact, effectively solving the problem of "invisibility." Second, empowerment at the analysis level drives the optimization of intelligent decision-making. Based on intelligent decision-making systems, digital technology can analyze the complex relationships among multiple constraints such as costs, resource consumption, and pollution emissions, promoting the development of resource allocation decisions toward intelligence, reshaping the internal logic of coordinated optimization of resources and environment, breaking through the zero-sum game dilemma between emission reduction and efficiency improvement, and fundamentally addressing the challenge of "incalculability." Third, empowerment at the execution level achieves precise real-time control of pollution. By deeply embedding real-time control systems into key nodes of the production process (such as core equipment and emission outlets), digital technology transforms pollution governance models from passive, extensive post-event treatment to active, precise millisecond-level prevention and closed-loop control, directly solving the core problem of "uncontrollability" in end-of-pipe governance. Based on this, research hypothesis H1 is proposed.

H1: Digital technology can enable traditional manufacturing to achieve green transformation.

2.2 The "Compensation Effect" of Green Fiscal Policy

Ecological compensation theory emphasizes correcting the imbalance of positive environmental externalities through fiscal instruments to achieve the fair efficiency of "beneficiary pays, protector receives compensation." As an expenditure-type policy tool, green fiscal policy can effectively correct the distortion of resource allocation, and its core lies in exerting the "compensation effect"—that is, internalizing the social spillover of digital technology's green benefits and systematically compensating for the imbalance between enterprise green upgrading revenues and expenditures. First, in the dimension of ecological value compensation, the ecological benefits generated by enterprise green transformation—such as air quality improvement and biodiversity protection—are shared by the whole society. However, the additional costs involved in the green transformation process, such as equipment updates and technology R&D, must be borne by enterprises themselves, severely weakening the motivation of market entities to promote green transformation (Liu, J. L., & Chen Y. Y., 2024a). Fiscal subsidies fill the high investment gap during the enterprise's digital-green synergistic application period by providing substantive economic compensation, effectively solving the problem of positive externality loss caused by market failure. Second, in the dimension of technical knowledge compensation, digital technology has good integrated empowerment advantages, but its natural sharing and mobility attributes also lower the threshold for other entities to learn and imitate. Transformation subjects often need to pay a great price to complete long-cycle green technology R&D; however, external competitors can absorb existing clean technologies through "free-riding," resulting in an obvious asymmetry between R&D achievements and actual benefits (Jamaani, & Ahmed, 2020). Patent fees recover imitation benefits to fiscal funds, while fiscal subsidies redistribute innovation benefits to original enterprises through precise targeting, effectively improving the economic expectations of green technology iteration, thereby amplifying the overall enabling effect of digital technology on green transformation. Based on this, research hypothesis H2 is proposed.

H2: Green fiscal policy can significantly amplify the enabling effect of digital technology on the green transformation of traditional manufacturing.

2.3 The "Cost Effect" of Green Taxation

Based on Pigouvian tax and externality theory, the core of green taxation lies in exerting the "cost effect"—that is, by imposing additional taxes on polluters, forcing the internalization of negative pollution externalities into private costs, compelling enterprises to carry out green technology transformation. First, in terms of forced emission reduction, China's green taxation system, with the environmental protection tax as the core, has shaped the cost constraints of "who pollutes, who pays," forcing enterprises to weigh pollution costs and transformation benefits. Empirical evidence shows that with the increase in environmental protection tax rates, pollution-intensive enterprises significantly reduce pollutant emissions (Lakhal, & Dedaj, 2020). Second, in terms of innovation incentives, the "Porter hypothesis" suggests that appropriately designed environmental regulations can stimulate enterprise innovation. Green taxation, through the "cost effect" mechanism, compels traditional manufacturing enterprises

to shift from end-of-pipe treatment to source prevention and whole-process control. Compared with simple command-and-control regulatory means, the tax system design with gradually increasing marginal costs not only curbs enterprises' opportunistic behavior of superficial end-of-pipe pollution treatment but also improves the quality and efficiency of green innovation, driving enterprises to break path dependence and achieve substantive transformation toward digital green production models. Based on this, research hypothesis H3 is proposed.

H3: Green taxation can significantly amplify the enabling effect of digital technology on the green transformation of traditional manufacturing.

3. Research Design

3.1 Model Construction

To test the impact of digital technology on the green transformation of traditional manufacturing, a high-dimensional fixed effects econometric model is constructed as follows:

$$GT_{it} = \alpha_0 + \alpha_1 DT_{it} + \sum \beta_j Control_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where i represents the province and t represents the year. GT_{it} represents the level of green transformation of traditional manufacturing in province i in year t , DT_{it} represents the level of digital technology development in province i in year t , $Control_{it}$ is the set of control variables, μ_i is the provincial fixed effect, λ_t is the time fixed effect, and ε_{it} is the random disturbance term.

3.2 Variable Definitions

(1) Dependent Variable: Green Transformation of Traditional Manufacturing (GT)

Currently, academia has not formed a clear and unified conceptual connotation and industry boundary for traditional manufacturing. According to the classification of traditional manufacturing proposed in the "Guiding Opinions on Accelerating the Transformation and Upgrading of Traditional Manufacturing" jointly issued by the Ministry of Industry and Information Technology and seven other departments, referring to the key development areas mentioned in the "Made in China 2025" plan, and based on the current "Industrial Classification for National Economic Activities" (GB/T 4754-2017), 20 industries including textiles, light industry, petrochemical and chemical, steel, and non-ferrous metals are defined as traditional manufacturing (Li and Ruan, 2024). Existing literature on "green transformation" mainly uses single indicators such as energy consumption intensity, pollution emission intensity, green patents, industrial structure upgrading index, and economic-energy decoupling value, or the DEA method for measurement (Long et al., 2023). As an important part of high-quality manufacturing development, the connotation of green transformation of traditional manufacturing is not only reflected in resource utilization intensification, pollutant emission reduction, environmental impact reduction, productivity improvement, and sustainable development enhancement, but should also cover the improvement of organizational systems and the enhancement of production efficiency. To this end, combined with the new requirements for "transforming and upgrading traditional industries" proposed in important documents such as the "14th Five-Year Plan for Industrial Green Development" and

the guiding opinions jointly issued by multiple departments including the Ministry of Industry and Information Technology, first-level indicators are constructed from five dimensions: energy conservation and emission reduction, structural optimization, technological innovation, green system, and quality and efficiency improvement, and further expanded to 12 second-level indicators and 30 third-level indicators. The entropy method is used to comprehensively measure the green transformation level of traditional manufacturing in each province from 2011 to 2022.

(2) Independent Variable: Digital Technology (DT)

Digital technology is a combination technology covering information processing, computing power, communication means, and connectivity (Liu, & Chen, 2024), mainly including digital components, digital platforms, and digital infrastructure. Its essence lies in the large-scale, intelligent collection, production, and use of information. Currently, domestic digital technology is still in the preliminary development stage, and there is no consensus on the measurement of digital technology. According to policy documents such as the "Overall Layout Plan for Digital China Construction" and the "14th Five-Year Plan for Digital Economy Development" issued by the Central Committee of the Communist Party of China and the State Council, the development process of digital technology should meet the "five needs": digital infrastructure needs to be gradually improved, the value of digital elements needs to be effectively released, digital technology applications need to be expanded in multiple areas, digital technology innovation needs to accelerate breakthroughs, and the digital development environment needs to be gradually optimized. Based on this, from five dimensions—digital infrastructure, digital factor input, digital technology application, digital technology innovation, and digital environment—a total of 20 differentiated indicators are selected to comprehensively evaluate the digital technology development level of each province.

(3) Mechanism Variables

a) Green Fiscal Policy (GF)

The positive externality of digital technology enabling green transformation makes the overall social marginal cost lower than the enterprise's private marginal cost. This imbalance of cost and benefit can easily weaken the endogenous motivation of market entities for green transformation. Green fiscal policy incorporates green and environmental protection attributes into the traditional fiscal system. It is an important signal reflecting the green policy orientation of governments at all levels, can directly support ecological civilization construction through fiscal means, and provide sufficient funding guarantees for enterprise green transformation. Among them, the environmental protection investment of the public sector can directly quantify the extent to which local governments tilt fiscal resources toward environmental governance, objectively reflect the implementation intensity of green fiscal policies, and is an important manifestation of government support for green development, playing a crucial role in improving resource utilization efficiency and reducing environmental pollution. Therefore, the proportion of environmental protection-related expenditures disclosed in each province's statistical yearbook to local fiscal expenditures (Ong, Mohd-Rashid, & Taufil-Mohd, 2021) is used as a proxy indicator for provincial green fiscal policy intensity.

b) Green Taxation (GTax). The concept of green taxation originated from "Pigouvian tax," advocating the use of taxation to achieve "internalization of external costs," thereby achieving the purpose of curbing pollution and protecting the environment. In essence, it constrains the pollution emission behavior of market entities by increasing production costs. Narrowly defined green taxation specifically refers to tax policies formulated by the government for pollution prevention and control. Domestic research mostly uses environmental protection tax (pollution fee) as the core characteristic variable. However, with the deepening of the industrial process and the continuous increase of environmental pressure, a single environmental protection tax can no longer meet the growing demand for emission reduction. In contrast, broadly defined green taxation emphasizes the symbiotic development between ecology and economy, covering a series of tax policies that directly or indirectly affect natural environmental protection and rational utilization of natural resources. In addition to environmental protection tax, it also includes the collection of resource tax, consumption tax, etc., which can not only internalize the negative externality of enterprise ecological environment pollution but also more comprehensively reflect the greening degree of China's taxation. Therefore, tax types with greening functions including consumption tax, resource tax, environmental protection tax, pollution fee, vehicle and vessel tax, vehicle purchase tax, urban maintenance and construction tax, urban land use tax, and farmland occupation tax are selected to measure regional green tax revenue, and the natural logarithm of green tax revenue is taken to reduce heteroscedasticity.

(4) Control Variables

Economic development level, urbanization level, industry scale, technological innovation, environmental regulation, and human capital can all affect the degree of green transformation of traditional manufacturing. Considering data availability and indicator endogeneity, the following control variables are ultimately selected: economic development level (PGDP), measured by the natural logarithm of per capita GDP after deflation; urbanization level (URB), measured by the ratio of urban population to total regional population (Rousseuw, & Leroy, 2005); industrial structure (IND), represented by the proportion of secondary industry added value to regional GDP; openness degree (OPEN), expressed by the ratio of total goods import and export (converted by exchange rate) to regional GDP; population density (POPD), measured by the natural logarithm of the ratio of total regional population to regional administrative area; and financial development level (FIN), measured by the ratio of year-end deposit and loan balance of financial institutions to regional GDP.

3.3 Data Sources

The research period is set from 2011 to 2022. To ensure data comparability, all data are standardized, and each continuous variable in the model is winsorized at the 1% level to reduce the interference of outliers. Relevant data come from the China Statistical Yearbook, China Industrial Statistical Yearbook, China Fiscal Statistical Yearbook, China Environmental Statistical Yearbook, etc.

Descriptive statistics (Table 1) show that the overall level of green transformation of traditional manufacturing is relatively low with significant spatial differences. Its maximum value (0.268)

is close to four times the mean value (0.052), indicating that most provinces still face a "pollution lock-in" dilemma. At the same time, the right-skewed distribution of digital technology (mean 0.182, median 0.053) also reflects regional differences in digital elements, with a few provinces possibly having formed digital innovation clusters while the vast majority of regions are still in the "digital depression." In comparison, the distribution of green fiscal policy is relatively balanced, but the standard deviation of green taxation is large, indicating significant differences in emission intensity among regions, with a typical "big polluter" phenomenon. The distribution of control variables is basically in line with expectations, showing no significant differences compared with existing research.

Table 1. Descriptive Statistics

Variable	Symbol	N	Mean	Median	Std Dev	Min	Max
Green Transformation	GT	360	0.052	0.053	0.032	0.078	0.254
Digital Technology	DT	360	0.182	0.097	0.216	0.046	0.734
Green Fiscal Policy	GF	360	0.031	0.026	0.054	0.012	0.24r
Green Taxation	GTax	360	6.002	6.067	0.942	4.424	7.241
Economic Development	PGDP	360	10.135	10.660	0.238	9.564	11.523
Urbanization	URB	360	0.359	0.566	0.061	0.350	0.521
Industrial Structure	IND	360	0.321	0.369	0.063	0.162	0.512
Openness	OPEN	360	0.156	0.121	0.215	0.046	1.459
Population Density	POPD	360	7.432	7.621	0.431	5.745	8.491
Financial Development	FIN	360	3.432	3.154	1.054	1.517	6.282

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively. Robust standard errors are in parentheses.

4. Empirical Results and Analysis

4.1 Baseline Regression Analysis

Before regression, the variance inflation factor (VIF) was used to test multicollinearity among variables. The results show that the VIF values among variables range from 1.27 to 4.15,

indicating that the model does not have serious multicollinearity problems. The unit root test results show that all variables strongly reject the null hypothesis of "having a unit root," indicating that the series is stationary and can be directly included in the regression analysis.

The results show that the regression coefficient of digital technology is consistently positive and passes the 1% significance level test, confirming its enabling effect on the green transformation of traditional manufacturing, thus H1 is verified. This enabling effect mainly originates from IoT energy efficiency improvement, blockchain carbon footprint tracking, and AI pollution control efficiency improvement. With the deep application of new infrastructure, these technical means build a complete transformation support framework by extending product lifecycles and strengthening digital management and control of environmental performance, providing systematic solutions for the sustainable development of traditional manufacturing.

4.2 Mechanism Testing

The optimal allocation of green fiscal and tax policies is crucial for China's current environmental governance. To test the independent effects and policy combination mechanisms of green fiscal and tax policies in the process of digital technology enabling the green transformation of traditional manufacturing, interaction terms of digital technology and green fiscal and tax policies are introduced on the basis of model (1) to test the moderating effects of policy interaction. The econometric models are constructed as follows:

$$GT_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 GF_{it} + \beta_3 DT_{it} \times GF_{it} + \sum \gamma_j Control_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

$$GT_{it} = \gamma_0 + \gamma_1 DT_{it} + \gamma_2 GTax_{it} + \gamma_3 DT_{it} \times GTax_{it} + \sum \delta_j Control_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

$$GT_{it} = \delta_0 + \delta_1 DT_{it} + \delta_2 GF_{it} + \delta_3 GTax_{it} + \delta_4 DT_{it} \times GF_{it} + \delta_5 DT_{it} \times GTax_{it} + \delta_6 DT_{it} \times GF_{it} \times GTax_{it} + \sum \zeta_j Control_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

(1) The "Compensation Effect" of Green Fiscal Policy. The independent effect of green fiscal policy is not statistically significant, while the interaction term of digital technology and green fiscal policy (DT×GF) has a positive coefficient and passes the 5% significance level test, indicating that green fiscal policy, as an "efficiency enhancer," can strengthen the enabling effect of digital technology on the green transformation of traditional manufacturing, basically verifying H2. The underlying mechanism is that in the absence of digital technology support, green fiscal funds may be difficult to allocate effectively due to insufficient enterprise technical capacity, manifesting as an insignificant independent effect. However, when digital technology interacts with green fiscal policy, fiscal funds can be precisely allocated, and the market risks and technical uncertainties of digital technology R&D are effectively mitigated, significantly improving enterprise innovation resilience and transformation efficiency.

(2) The "Cost Effect" of Green Taxation. The results show that the interaction term of digital technology and green taxation (DT×GTax) is significantly positive at the 1% level, while the independent effect of green taxation does not pass the significance test. This indicates that green taxation can significantly enhance the enabling effect of digital technology on the green transformation of traditional manufacturing, and the exertion of this moderating effect is highly

dependent on the application of digital technology. Thus, H3 is verified. From the perspective of the mechanism, green taxation internalizes environmental negative externalities through policy tools such as environmental protection tax and carbon tax, directly raising the marginal cost of pollution emissions for economic entities. In this process, the "differential treatment" of financial institutions forces traditional manufacturing enterprises to choose between paying for pollution and upgrading technology, compelling them to increase green innovation investment through high compliance costs. Under the cost constraint of market clearing, high-pollution, low-efficiency traditional production methods are gradually phased out, ultimately forming a benign development path of digital technology enabling the green transformation of traditional manufacturing.

(3) The Combined Effect of Green Fiscal and Tax Policies. The coefficient of the interaction term of digital technology and green fiscal and tax policies ($DT \times GF \times GTax$) is significant at the 5% level, but compared to the single policy effects (0.012 and 0.198), the regression coefficient of the policy combination effect is somewhat weakened (0.081). This phenomenon can be explained from two dimensions: policy complementarity and implementation friction. At the policy synergy level, the long-term technology incentives of green fiscal policy may induce a "surface innovation" orientation, while the regulatory constraints of green taxation inhibit rent-seeking space. At the same time, the compliance costs of green taxation may inhibit innovation investment, while the subsidies of green fiscal policy alleviate this pressure, forming benign complementarity between the two. At the policy implementation level, green fiscal policy requires proof of technological advancement, while green taxation emphasizes the actual effectiveness of emission reduction. However, the application of advanced technology is often accompanied by increased energy consumption, and implementation conflicts between policy tools may lead to institutional friction. This internal tension makes the policy combination effect present a suboptimal state of " $1+1 < 2$," reflecting the typical dilemma in policy tool synergy.

4.3 Endogeneity Tests

(1) Instrumental Variable Method. To address the possible bidirectional causal relationship between digital technology and the green transformation of traditional manufacturing, the instrumental variable method is used to handle endogeneity issues. The interaction term of each province's 1984 postal and telecommunications business volume and the previous period's national information technology service income is used to construct the instrumental variable (Li & Ruan, 2024). This instrumental variable strictly satisfies the correlation and exogeneity conditions. From the correlation perspective, regional information technology level directly affects the degree of digital technology integration and penetration. From the exogeneity perspective, the frequency of use of postal and telecommunications services in daily production has been declining year by year, and the 1984 postal and telecommunications business volume is historical data that does not directly impact the current period. The results show that the instrumental variable (IV) and its policy interaction terms all pass the under-identification and weak instrumental variable tests, and the first-stage instrumental variables are positively significant (IV, $IV \times GF$, and $IV \times GTax$ all pass the 1% significance test). At the same time, the impacts of each endogenous variable in the model (core explanatory

variable DT, policy interaction terms $DT \times GF$ and $DT \times GTax$) on the green transformation of traditional manufacturing at least pass the 10% significance test, thereby corroborating the accuracy of the research conclusions.

(2) Dynamic System GMM Test. To overcome the limitations of the fixed effects model in handling the endogeneity of time-varying factors, the estimation method was further replaced, and the dynamic system GMM model was used for re-estimation. The results show that the estimated coefficient of digital technology (DT) is significant at least at the 5% level, and the interaction term coefficients with green fiscal policy and green taxation ($DT \times GF$, $DT \times GTax$) all pass the 10% significance test. After controlling for dynamic panel bias, the core conclusions remain robust.

4.4 Robustness Tests

(1) Lagged Explanatory Variables. Considering the time-lag characteristics of the enabling effect of digital technology, the digital technology indicator lagged by one period is introduced for robustness testing. The results show that the regression coefficient of the lagged one-period digital technology indicator is highly consistent with the baseline regression results in terms of direction and statistical significance, indicating that the enabling effect of digital technology on the green transformation of traditional manufacturing has continuity and robustness. This effect does not weaken with time lag, further verifying the reliability of the research conclusions.

(2) Exclusion of Special Samples. Considering the particularity of municipalities in terms of administrative hierarchy, economic development, and technological innovation, as well as the potential impact of external environmental changes during special periods on digital technology application and green fiscal and tax policies, a dual control strategy is adopted in the robustness test. On the one hand, sample data from four municipalities are excluded; on the other hand, specific annual observations subject to obvious external shocks are excluded, and regression estimation is performed again. The results show that the significance and coefficient magnitude of the key core variables do not change significantly, further verifying the robustness of the baseline regression results.

4.5 Heterogeneity Analysis

(1) Strategic Regional Heterogeneity. China has a vast territory, and influenced by factors such as natural resource distribution and labor mobility, the level of digital technology acceptance and application naturally differs among regions, which may lead to different effects on the green transformation of traditional manufacturing. To this end, the sample is divided into "four major strategic regions" and "non-four major strategic regions" for group testing of the enabling effects of digital technology based on regional heterogeneity. The regression results show that digital technology exhibits significant enabling effects in both types of regions, and the coefficient value of the "four major strategic regions" is larger. This difference may originate from the comprehensive infrastructure and strong technology absorption capacity of the "four major strategic regions," enabling them to more effectively transform cutting-edge technologies such as artificial intelligence and blockchain into transformation momentum. At

the same time, the moderating effect of green taxation is only significant in strategic regions, confirming the synergistic effect between policy tools and regional development levels. However, the moderating effect of green fiscal policy shows the opposite regional characteristics, with the "non-four major strategic regions" exhibiting stronger green fiscal moderating effects. The reason is that the "four major strategic regions" bear multiple national missions leading to dispersed policy resources, while the "non-four major strategic regions" face more urgent transformation pressure and are therefore more sensitive to policy incentives.

(2) Policy Background Heterogeneity. The implementation of the "Broadband China" strategy has provided key policy impetus for digital infrastructure upgrading. To test whether this policy environment has led to phased differences in the enabling effects of digital technology, the sample period is divided into pre-policy (2011–2014) and post-policy (2015–2022) stages for group testing. The results show that before policy implementation, the direct impact and mechanism of digital technology on the green transformation of traditional manufacturing were not statistically significant. However, after policy implementation (2015–2022), the estimated coefficients are all positive and pass the 1% significance level test. This is mainly because before the implementation of the "Broadband China" strategy, digital technology development lacked systematic policy support, leading to slow technological upgrading and insufficient industrial integration, resulting in minimal enabling effects on green transformation, and the transmission mechanism of green fiscal and tax policies was also hindered. After the implementation of the "Broadband China" policy, the rapid improvement of digital infrastructure effectively bridged the "digital divide" among enterprises, provided key support for green technology exchange and clean production R&D, and effectively advanced the green transformation process of traditional manufacturing.

5. Extended Analysis

Smart platforms driven by digital technology achieve exponential accumulation of data assets and value appreciation through the accumulation of user nodes. This dynamic process manifests as: digital technology development promotes organizations to continuously absorb, integrate, and optimize incremental data resources, constantly expand platform boundaries, attract more users and complementary entities to participate, and ultimately iterate and aggregate into powerful digital networks. Given that differences in digital technology application intensity lead to structural changes in enabling effects, panel quantile regression is used to examine the differentiated impact effects of digital technology on the green transformation of traditional manufacturing under different quantile conditions. Three typical quantile points—0.25, 0.50, and 0.75—are selected to construct the following econometric model:

$$Q\tau(GT_{it}) = \alpha\tau + \beta_{1\tau}DT_{it} + \beta_{2\tau}GF_{it} + \beta_{3\tau}DT_{it} \times GF_{it} + \beta_{4\tau}GTax_{it} + \beta_{5\tau}DT_{it} \times GTax_{it} + \Sigma\gamma_j\tau Control_{it} + \mu_i\tau + \varepsilon_{it}\tau$$

Where τ represents the quantile point. $\beta_{1\tau}$ reflects the impact of digital technology application on the green transformation of traditional manufacturing under each quantile condition. The meanings of other variables are the same as above.

The estimation results based on the panel quantile regression of digital technology show: (1) Digital technology exhibits significant enabling effects on the green transformation of traditional manufacturing at all quantile points, and its regression coefficient shows an increasing trend as the quantile point rises, confirming the superimposed empowerment characteristics of digital technology's "network effect." (2) The positive moderating effect of green taxation also shows a marginal benefit increasing trend, indicating that policy effectiveness is positively affected by the scale effect of digital technology. This suggests that in the low quantile range, higher digital technology application learning costs constrain the policy effect of green taxation; however, as the "learning by doing" effect deepens, the increase in digital factor penetration rate significantly enhances policy implementation effects, forming a benign interaction between technology and institutions. (3) The moderating effect of green fiscal policy shows a significant weakening characteristic as the level of digital technology application deepens (0.068, 0.045, 0.026), and when digital technology is at the 75% quantile point, the technology incentive effect of green fiscal policy is no longer statistically significant. This phenomenon may originate from the "technology path lock-in" effect. When enterprise digital transformation ventures into deepwater areas, the difficulty of technological breakthroughs increases exponentially, and the marginal incentive effect of fiscal subsidies can hardly cover the high-risk technology trial-and-error costs, ultimately leading policy tools to fall into an "innovation trap."

The quantile regression trend chart shows that as the digital technology quantile point rises, the coefficients of both digital technology and green taxation show a monotonically increasing trend, with their 95% confidence intervals consistently located above zero, confirming the significant "law of increasing marginal returns" for both. In stark contrast, the estimated coefficient of green fiscal policy continuously decays as the quantile point increases, and the confidence interval at high quantile points covers zero. This divergent trend indicates that when enterprise digital technology capabilities cross the critical threshold, the compensation effect of green fiscal policy exhibits "incentive saturation" characteristics. The gap between technological capability leap and policy tool adaptability leads to the gradual failure of original incentives.

6. Conclusions and Recommendations

As the institutional foundation and core pillar of national governance, green fiscal and tax policies provide new ideas and methods for digital technology to enable the green transformation of traditional manufacturing, becoming an "accelerator" for achieving the "dual carbon" goals. Using provincial panel data from 2011 to 2022 as a sample, this paper deeply analyzes the enabling effect of digital technology on the green transformation of traditional manufacturing and the moderating mechanism of green fiscal and tax policies. The results show that: digital technology significantly promotes the green transformation of traditional manufacturing; as regulatory instruments, green fiscal and tax policies play a positive moderating role in the digital technology enabling process through the "compensation effect" and "cost effect" mechanisms respectively, but the policy nesting of the two creates institutional friction, leading to a decline in enabling efficiency; the moderating effects of green fiscal and tax policies are more significant after the implementation of the "Broadband

China" policy, and green fiscal and tax policies exhibit policy attribute differences due to regional heterogeneity; the enabling effect of digital technology has "network effects," with technology lock-in occurring at high quantiles, and the technology compensation of green fiscal policy is gradually diluted.

Based on the above conclusions, the following policy recommendations are proposed:

First, focus on the full-chain empowerment of digital technology and build an intelligent foundation for the green transformation of manufacturing. At the perception level, establish a national-level manufacturing carbon footprint tracking and monitoring platform. Mandatorily require high-energy-consuming enterprises to be equipped with IoT monitoring devices and use blockchain technology for evidence management of relevant data. For micro, small, and medium enterprises, provide "Digital Carbon Steward" subsidies and implement differentiated pollution control strategies based on enterprise scale. At the analysis level, build regional-level industrial intelligent decision-making centers and open-source multi-objective optimization algorithm libraries to lower technical thresholds, promote the interconnection of digital element underlying logic, and improve the efficiency of green technology innovation. At the execution level, promote the digital and information-based certification mechanism of green assets, establish a green digital asset trading platform through technical means, and convert blockchain-certified emission reductions into pledgeable carbon assets. At the same time, implement the "Digital Green Voucher" system to continuously clear the technological empowerment cycle.

Second, reconstruct the dynamic synergy mechanism of green fiscal and tax policies to release the dual policy effectiveness of incentive-compatibility constraints. First, implement a quantile governance model for fiscal subsidies. Provide full equipment purchase subsidies and bet-type rewards for enterprises with digitalization levels at medium-low quantiles to encourage them to expand the scope of digital technology application. For high-quantile enterprises, focus on implementing additional deduction policies for core green technologies, thereby breaking through the bottleneck of weak fiscal incentives. Second, in the field of green taxation, continue to deepen tax system reform, establish a "Tax Refund Innovation Fund Pool," and use a flexible tax system with multi-tax co-governance to standardize the application of the regulatory means of "cost constraints." Third, reasonably balance various policy combinations, launch "Digital Green Packages," and allow fiscal reward funds to directly offset environmental protection taxes, using cost hedging to reduce enterprise transformation burdens, minimize institutional friction generated by policy combinations, and enhance policy synergy effectiveness.

Third, implement gradient regional governance strategies to break through the dilemma of policy response heterogeneity. On the one hand, the four major strategic regions need to highlight their technology leadership position, use Internet carbon tracking nodes to achieve cross-provincial data mutual recognition, connect cross-border trade activities with "Enterprise Digital Green Credit Scores," and effectively utilize the digital dividends of factor agglomeration areas to fully promote the green transformation of traditional manufacturing. On the other hand, non-strategic regions should focus on consolidating digital infrastructure

construction. Through the implementation of the "One Chain, One Cloud" project, establish a "tax depression" correction mechanism, and vigorously promote the "Digital Enclave" development model—that is, after enterprises in underdeveloped regions establish R&D enclaves in developed regions, they can enjoy dual-region rewards. Furthermore, use fiscal and tax spillovers to drive underdeveloped regions to achieve leapfrog upgrading of digital elements, bridge the digital divide generated in the green transformation process through targeted expansion of industrial internet bandwidth, and ultimately achieve coordinated regional green transformation.

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