

The Internal Mechanism of How Enterprise Digitalization Empowers Sustainable Development: A Mediation Analysis Based on Enterprise Green Transformation

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Abstract. Against the background of the integration of the "Dual Carbon" goals and the digital economy, this paper focuses on the internal mechanism of enterprise digital transformation empowering sustainable development. Based on the panel data of A-share listed companies from 2020 to 2024, this paper constructs a theoretical model of "digital transformation – green transformation – sustainable development". The findings show that: (1) Enterprise digital transformation can directly and significantly improve ESG performance; (2) It indirectly promotes sustainable development by facilitating green transformation, and green transformation plays a partial mediating role. The conclusions remain valid after robustness tests such as changing the measurement of the explained variable and shortening the sample interval. This paper systematically reveals the synergy mechanism between digitalization and greening, and provides empirical evidence for enterprises and policy makers to promote the "digital-green integration".

Keywords: Digital Transformation, Green Transformation, Sustainable Development, ESG

1. Introduction

Against the dual background of the "Dual Carbon" goals and the vigorous development of the digital economy, enterprise sustainable development has become a core issue of social economy. The Report to the 20th National Congress of the Communist Party of China also clearly proposes to "accelerate the green transformation of the development mode", which points out the direction for the sustainable development of enterprises, and enterprise digital transformation plays a pivotal role. Under the condition of in-depth integration and coordinated development of enterprise digitalization and greening, it provides a feasible path for enterprises to realize the collaborative improvement of economic, environmental and social values. As the core driving force for reshaping enterprise production and operation modes, digital transformation breaks through traditional development bottlenecks through the efficient flow of data elements. Its "resource effect" can optimize resource allocation and reduce innovation risks, and its "signaling effect" can attract external investment and ease financing constraints [1], injecting endogenous impetus into green transformation. As a key path for enterprises to break resource and environmental constraints, green transformation is the core link connecting digitalization and sustainable development [2]. However, the dual constraints of the

"digital divide" and "green barriers" are still severe: for some enterprises, digital transformation is difficult to convert into green development momentum due to the lack of effective implementation paths, and green transformation is hard to advance continuously due to resource constraints and technical bottlenecks. How to open up the synergy channel between the two and solve the development dilemma has become a key proposition for enterprises to practice the concept of sustainable development. Therefore, exploring how enterprise digital transformation empowers sustainable development, breaking through dual barriers, and realizing the collaborative improvement of economic, environmental and social values is not only an urgent need to respond to policy orientation and solve the practical dilemmas of enterprise development, but also an important exploration to enrich the theoretical system of sustainable development and clarify the synergy mechanism between digitalization and greening.

Existing studies have initially confirmed the deep correlation between digital transformation, green transformation and sustainable development. In terms of direct driving effect, scholars have empirically found that with efficient data integration and analysis capabilities, digital technologies break the dependence on traditional technology paths, optimize the allocation of green innovation resources [3], reduce innovation risks and information search costs, and significantly improve the efficiency and level of green innovation [4]. Digital transformation can also directly promote the collaborative improvement of enterprise environmental performance, economic performance and green innovation performance by monitoring production processes in real time and optimizing energy utilization efficiency [4]. In terms of mediating mechanism, existing studies have identified multiple transmission paths: green technology innovation [5] and green management innovation [6] are important mediators. Many scholars also point out that there are close connections and positive promoting effects between green innovation and digital transformation, as well as between green innovation and ESG [7, 8]. However, existing research still has shortcomings: most studies focus on single mediation test, lacking systematic analysis of green transformation as a multi-dimensional comprehensive mediator, and the discussion on heterogeneity and boundary conditions such as enterprise property rights and regional environmental regulation is not in-depth enough [9, 10].

To sum up, taking A-share listed companies from 2020 to 2024 as samples, this paper constructs a theoretical analysis framework of "digital transformation – green transformation – sustainable development", focusing on exploring the mediating mechanism of green transformation. The marginal contributions of this paper are as follows: First, it systematically analyzes the mediating effect of green transformation in digitalization empowering sustainable development, and refines the transmission chain of "resource integration – technological innovation – performance improvement". Second, combined with the dual attributes of ESG and supply chain characteristics, it reveals the heterogeneous impact of digitalization empowering sustainable development. Third, it provides empirical reference for enterprises to formulate coordinated development strategies of digitalization and greening, and for policy makers to improve relevant support systems.

2. Theoretical analysis

2.1. Enterprise digital transformation and ESG performance

The breakthrough development of digital technologies provides a new empowering path for enterprise ESG construction. Digital transformation promotes sustainable development from the three dimensions of environment, society and governance by reconstructing enterprise operation modes and optimizing resource allocation efficiency [11]. In the environmental dimension, digital transformation realizes precise monitoring of production processes and energy consumption

optimization with technologies such as big data and the Internet of Things, reduces pollution emissions and improves resource recycling efficiency, and directly improves environmental performance. In the social dimension, digital tools break information barriers, strengthen the interaction and collaboration between enterprises and stakeholders such as employees, customers and communities, and help enterprises efficiently fulfill social responsibilities. In the governance dimension, digital transformation optimizes enterprise decision-making processes and supervision mechanisms, and reduces agency problems [12]. Enterprise digital transformation can also lay a foundation for ESG performance improvement and provide institutional guarantee for ESG practice by improving information transparency and easing financing constraints [13].

H1: Enterprise digital transformation has a significant positive impact on ESG performance.

2.2. Enterprise digital transformation and green transformation

Green transformation is a dynamic process in which enterprises integrate the concept of green development into the whole process of production and operation to achieve energy conservation, emission reduction, quality improvement and efficiency enhancement, covering the multi-dimensional improvement of environmental performance, economic performance and green innovation performance. Relying on the innovative application of digital technologies and the value release of data elements, digital transformation has become the core force driving enterprise green transformation, and consolidates the technical and resource foundation for its full-process implementation and multi-dimensional performance improvement. Digital transformation provides core driving force for green transformation, and its mechanism is reflected in three aspects: First, the resource orchestration effect. Digitalization optimizes resource allocation through the efficient flow of data elements, and eases the capital and technical constraints faced by green transformation [14]. Second, the technology empowerment effect. Digital technologies are deeply integrated with green technologies to promote green process innovation and the implementation of clean production modes. Third, the external supervision effect. Digitalization improves the transparency of enterprise information disclosure, attracts the attention of external subjects such as investors and media, and forces enterprises to strengthen the impetus of green transformation [4]. From the above three aspects, it can be concluded that digital transformation can significantly promote enterprise green transformation through paths such as improving internal capabilities, enhancing market attention and obtaining government subsidies (external supervision).

H2: Enterprise digital transformation has a significant positive impact on green transformation.

2.3. The mediating role of green transformation

Green transformation plays a key mediating role between digital transformation and ESG performance, constructing a transmission chain of "digital empowerment – green transformation – ESG improvement". From the environmental dimension, green transformation directly improves enterprise environmental performance through practices such as pollution control and clean production, and becomes the core support of ESG scores. From the social dimension, behaviors such as green supply chain collaboration and environmental responsibility fulfillment formed in the process of green transformation enhance the trust of stakeholders and improve corporate social reputation [15]. From the governance dimension, green transformation requires enterprises to establish a sound environmental management system and risk prevention and control mechanism, forcing the improvement of governance level, and then optimizing the comprehensive ESG performance.

Existing studies show that green transformation is mainly reflected in core dimensions such as green technological innovation, environmental protection process optimization and green product research and development. As the core carrier of green transformation, green innovation can significantly mediate the relationship between digital transformation and ESG performance through specific manifestations such as green patent breakthroughs, energy-saving technology application and pollution control process upgrading [10]. The technological iteration and environmental efficiency improvement brought by green innovation not only directly promote the implementation of enterprise green transformation, but also further guarantee the improvement of ESG scores through the performance improvement and signaling effects [12].

H3: Enterprise green transformation has a significant positive impact on ESG performance.

H4: Enterprise green transformation plays a mediating role between digital transformation and ESG performance.

3. Research design

3.1. Variable selection

3.1.1. Explained variable: enterprise sustainable development level (ESG)

Referring to the research of Xie Hongjun and Lü Xue [13], this paper uses Huazheng ESG rating score to measure the level of enterprise sustainable development. Huazheng ESG rating covers three dimensions: environment, society and corporate governance. Through multi-channel data collection and quantitative evaluation, it forms a nine-level rating system from C to AAA, and the rating results have high objectivity and credibility. Referring to existing research practices, Huazheng ESG ratings are assigned values from 1 to 9 from low to high, and the annual average is taken as the proxy variable of enterprise sustainable development level. The higher the score, the better the enterprise sustainable development performance.

3.1.2. Explanatory variable: enterprise digitalization (digital)

Enterprise digital transformation is a systematic reform process in which enterprises take the accumulation and value transformation of data assets as the core, deeply apply digital technologies such as artificial intelligence, big data and cloud computing, integrate data resources and improve data processing capabilities. The essence of data assets is reflected in the actual precipitation of digital resources and the improvement of application efficiency, rather than simple technology investment disclosure, which is the core dimension to measure the actual level of enterprise digitalization. At present, the academic community mainly measures the degree of enterprise digital transformation based on the keyword frequency statistics method of annual reports of listed companies. It reflects the transformation investment by extracting the occurrence frequency of related characteristic words such as artificial intelligence, big data and cloud computing (adding 1 and taking natural logarithm) [16]. However, this measurement method still has certain limitations: the text word frequency method is easily affected by the difference of annual report disclosure caliber, and it is difficult to accurately capture the actual accumulation of digital resources. As the core achievement and key resource of enterprise digital transformation, data assets not only cover the application depth of digital technologies and the scale of data reserves, but also directly reflect the data processing and value transformation capabilities, which can more essentially reflect the actual level of digital transformation. Therefore, this paper takes the natural logarithm of enterprise

data assets as the core explanatory variable to measure the degree of enterprise digitalization. The original value of enterprise data assets is added by 1 and then processed by natural logarithm to alleviate the right-skewed characteristic of data distribution and more accurately reflect the actual level of enterprise digital transformation.

3.1.3. Mediating variable: enterprise green transformation (green)

Referring to the practice of Cai Lihui and Zhang Xiaolu [10], this paper uses the number of enterprise green invention patent applications to measure the effect of enterprise green transformation. Green invention patent applications have high technical thresholds and strong innovation, which can effectively avoid the interference of strategic innovation and directly reflect the substantive output of enterprises in the R&D and application of green core technologies. At the same time, the indicator data can be accurately obtained through the patent database, which is objective and comparable, and can stably reflect the quality and sustainability of enterprise green transformation [17]. Therefore, this paper uses the number of enterprise green invention patent applications to measure the effect of enterprise green transformation. This indicator directly reflects the innovation output of enterprises in the R&D and application of green technologies, and is a core indicator reflecting the depth and quality of green transformation, providing a more reliable measurement basis for revealing the internal mechanism of digitalization empowering sustainable development.

3.1.4. Control variables

To eliminate the interference of irrelevant factors on the empirical results, the following control variables are selected with reference to existing literature: (1) Return on total assets (ROA), expressed as the ratio of enterprise after-tax net profit to total enterprise assets, reflecting the impact of enterprise profitability on sustainable development. (2) Number of board members (Board), measured by the actual number of enterprise board members, to control the role of corporate governance structure on enterprise decision-making and sustainable development.

Table 1. Variable description

Variable Type	Variable Name	Variable Symbol	Variable Definition
Explained Variable	Enterprise Sustainable Development Level	ESG	Huazheng ESG Score - Annual Average
Explanatory Variable	Enterprise Digitalization	Digital	Natural logarithm of enterprise data assets
Mediating Variable	Enterprise Green Transformation	Green	Number of enterprise green invention patent applications
Control Variables	Return on Total Assets	ROA	Ratio of enterprise after-tax net profit to total enterprise assets
	Number of Board Members	Board	Actual number of enterprise board members

3.2. Data sources and descriptive statistics

Based on the original data of Shanghai and Shenzhen A-share listed companies from 2015 to 2024, combined with the policy cycle and data availability focused on by the research, this paper selects five consecutive years of panel data as research samples to ensure the continuity and timeliness of data during the observation period. According to the core explanatory variable (enterprise digital transformation), explained variable (enterprise sustainable development), mediating variable (enterprise green transformation) and control variables (such as return on total assets, number of board members) in the research design, the corresponding variable data are accurately extracted from databases such as CSMAR, Wind and CNRDS, and redundant variables irrelevant to the research topic are eliminated to simplify the data structure. In the process of data purification: (1) Delete observations with incomplete variable data. For enterprises with missing core variables and incomplete key financial and governance data, the whole sample is excluded to avoid the interference of missing values on regression results. (2) Eliminate redundant and invalid data, including observation samples with abnormal data and logical contradictions, to ensure the authenticity and reliability of the remaining data. Finally, a balanced panel data meeting the research requirements is formed, with a sample size of 3095, which lays a solid foundation for subsequent empirical analysis. The descriptive statistical results of the main variables are shown in the table below.

Table 2. Descriptive statistical results

Variable	Symbol	Observations	Mean	Standard Deviation	Maximum	Minimum
Enterprise Sustainable Development Level	ESG	3095	4.45	0.955	9	2
Enterprise Digitalization	Digital	3095	23.62	1.307	29	21
Enterprise Green Transformation	Green	3095	29.60	63.419	686	0
Return on Total Assets	ROA	3095	3.22	5.933	44	-39
Number of Board Members	Board	3095	8.47	1.692	16	4

4. Empirical analysis

4.1. Mediation effect test results

Taking A-share listed companies from 2020 to 2024 as samples, this paper constructs a mediation effect model of "digital transformation – green transformation – sustainable development" to empirically test the transmission role of green transformation between enterprise digitalization and ESG performance. The model fitting results show that the coefficients of core variables all pass the significance test at the 1% level, and the adjusted R^2 of the models are 0.157, 0.322 and 0.164 respectively. The overall fitting effect is good, which can effectively reveal the internal correlation between variables.

The total effect model directly examines the impact of enterprise digital transformation (Digital) on sustainable development level (ESG). The results show that the regression coefficient of digital

transformation is 0.361, which is significant at the 1% level ($t=20.829$, $P<0.001$), indicating that enterprise digital transformation has a significant positive driving effect on ESG performance, which verifies research hypothesis H1, that is, digital transformation can directly empower enterprise sustainable development.

The mediating variable model tests the impact of digital transformation on green transformation (Green). The regression results show that the coefficient of digital transformation is 0.579, passing the significance test at the 1% level ($t=37.227$, $P<0.001$), indicating that enterprise digital transformation can significantly promote green transformation, and research hypothesis H2 is confirmed. This result reflects that digital transformation provides a solid impetus for green transformation.

The direct effect results show that the direct effect coefficient of digital transformation on ESG performance is 0.302 ($t=14.513$, $P<0.001$), which is still significant at the 1% level. The regression coefficient of green transformation is 0.103 ($t=5.151$), which also passes the significance test at the 1% level. This indicates that green transformation plays a partial mediating role between digital transformation and ESG performance, and research hypotheses H3 and H4 are established, that is, digital transformation not only directly improves the level of enterprise sustainable development, but also forms an indirect transmission path by promoting green transformation.

Table 3. Mediation effect test results

Variable	Model 1: Total Effect	Variable	Model 1: Total Effect
Core Variables			
Digital	0.361***(20.829)	—	0.302***(14.513)
Green	—	0.579***(37.227)	0.103***(5.151)
Control Variables			
ROA	0.116***(6.827)	-0.142***(-9.343)	0.131***(7.614)
Board	-0.058***(-3.455)	0.023(1.501)	-0.061***(-3.608)
Model Fit			
Sample Size	3095	3095	3095
R ²	0.158	0.323	0.165
Adjusted R ²	0.157	0.322	0.164

Note: ***, **, * indicate $P<0.01$, $P<0.05$, $P<0.1$ respectively, and the values in parentheses are t-values. The same below.

4.2. Endogeneity and robustness tests

In empirical research, endogeneity problems may arise from factors such as the two-way causal relationship between explanatory variables and explained variables, and omitted variables, which in turn affect the consistency of estimation results. Meanwhile, to ensure the reliability and generalizability of research conclusions, it is necessary to verify the benchmark regression results through multi-dimensional robustness tests. Based on this, this paper carries out robustness tests from two dimensions: changing the measurement of the explained variable and shortening the sample interval to deal with endogeneity problems. The specific test process and results are as follows:

First, changing the measurement of the explained variable. Although Huazheng ESG evaluation system has the advantages of timely update, wide coverage of enterprises and prominent timeliness, it should be noted that there is no unified standard for ESG rating criteria, which are independently set by each rating agency. To avoid the subjective bias caused by the difference of scoring standards of different institutions, and eliminate the impact of a single rating agency, so as to ensure the fairness of the research and the objectivity of ESG performance evaluation, this paper draws on the practice of Yang Youde et al. [18] to replace Huazheng ESG score - annual average with Wind-ESG score. To verify the reliability of the benchmark regression conclusion, this paper adopts the method of replacing the explained variable to conduct robustness test, replaces the original explained variable "Huazheng ESG score - annual average" with "Wind-ESG score", and reconstructs the regression model for empirical analysis. The results show that the regression coefficient of the core explanatory variable enterprise digital transformation (Digital) is 0.324, which is significant at the 1% level ($t=15.649$, $P<0.001$), indicating that enterprise digital transformation still has a significant positive impact on the level of enterprise sustainable development. The above test results show that after changing the measurement method of the explained variable, the core conclusion that enterprise digital transformation positively drives sustainable development is still valid, and the benchmark regression results have strong robustness. The specific results are shown in Table 4 (1).

Second, shortening the sample interval. To further verify the reliability of the benchmark regression conclusion, referring to the practice of Liao Hongsu [19], this paper adopts the method of shortening the sample interval to carry out robustness test. After excluding the sample data of 2020, taking the panel data of A-share listed companies from 2021 to 2024 as research samples, the regression test is re-conducted on the mediation effect model of "digital transformation – green transformation – sustainable development". The results show that the regression coefficient of the core explanatory variable enterprise digital transformation (Digital) on the explained variable ESG performance is 0.317, which is significant at the 1% level ($t=13.599$, $P<0.001$), indicating that the positive driving effect of digital transformation on enterprise sustainable development is still significant. The regression coefficient of the mediating variable green transformation (Green) is 0.099 ($t=3.849$, $P<0.001$), which still passes the significance test, and its transmission path remains stable. The above test results show that after shortening the sample interval, the core conclusion of this paper that digital transformation empowers enterprise sustainable development through the mediation of green transformation has not changed, and the benchmark regression results have strong robustness. The specific results are shown in Table 4 (2).

Table 4. Endogeneity and robustness test results

	ESG	
	(1)	(2)
Core Variables		
Digital	0.324*** (15.649)	0.317*** (13.599)
Green	0.099*** (4.971)	0.086*** (3.849)
Control Variables		

Table 4. (continued)

ROA	0.069***(14.036)	0.143***(7.498)
Board	0.040***(2.420)	-0.061(-3.263)
Model Fit		
Sample Size	3095	2475
R ²	0.173	0.175
Adjusted R ²	0.172	0.173

5. Conclusions and recommendations

5.1. Conclusions

Taking A-share listed companies from 2020 to 2024 as samples, this paper constructs a theoretical and empirical analysis framework of "digital transformation – green transformation – sustainable development", systematically investigates the impact mechanism of digital transformation on enterprise sustainable development, and focuses on testing the mediating role of green transformation in it.

First, enterprise digital transformation has a significant direct driving effect on sustainable development. The data shows that for each unit increase in digital transformation, the average ESG score of enterprises increases by 0.361 units. This result indicates that digital transformation directly promotes the comprehensive performance of enterprises in environmental, social and governance dimensions through paths such as optimizing resource allocation, improving information transparency and improving governance structure [12]. In terms of resource allocation, digital transformation accurately matches green innovation elements by integrating internal and external data resources, reduces R&D and emission reduction costs, and promotes the low-carbonization of production processes [4]. In terms of governance structure, digitalization optimizes internal decision-making processes, alleviates agency conflicts, promotes the integration of ESG concepts into strategic planning, and strengthens the fulfillment of environmental and social responsibilities [16]. In the robustness tests of replacing the ESG evaluation system (switching to Wind-ESG score) and shortening the sample interval (2021—2024), the positive relationship is still significant (Table 4), which further confirms the reliability of the conclusion.

Second, green transformation plays a partial mediating role between digital transformation and sustainable development. Digital transformation not only directly improves ESG performance, but also forms an indirect transmission path of "digital transformation → green transformation → ESG improvement" by promoting green transformation. This mechanism essentially reflects a complete transmission chain of "resource – technology – supervision": digital transformation alleviates the resource constraints of green innovation through data element integration [14], and strengthens external supervision by improving information transparency [4]. Multiple paths jointly promote enterprise green transformation; green transformation further comprehensively improves ESG performance from the three dimensions of environment, society and governance through pollution control optimization, green supply chain collaboration and improvement of environmental

governance system [15], forming a closed-loop improvement mechanism for sustainable development.

5.2. Recommendations

First, enterprises should pragmatically promote the integration of digitalization and greening, take "key links" as breakthrough points, replace the "large and comprehensive" digital blueprint, and avoid the disconnection between digital investment and green goals. At the production end, big data can be used to optimize production scheduling, the Internet of Things can monitor energy consumption and emissions in real time, and parameters can be dynamically adjusted with artificial intelligence to reduce resource consumption and pollution emissions per unit output. At the supply chain end, blockchain can be used to build a green supply chain traceability system, open up upstream and downstream environmental protection data sharing channels, accurately screen low-carbon suppliers, and alleviate the problem of environmental information asymmetry. At the environmental governance end, digital tools can be used to solve management pain points. Cloud computing can integrate internal and external environmental protection data of enterprises, build an environmental protection decision support system, and automatically generate compliance reports and optimization suggestions. At the same time, mobile Internet can be used to build an environmental protection management APP, allowing employees to report environmental problems in real time, forming a closed loop of "discovery-feedback-rectification-tracking", and promoting the full implementation of environmental protection responsibilities.

Second, the enterprise management mechanism should be substantially tilted towards "green innovation", improve the incentive and research system, and guide resources to gather in green innovation. We should take the number of applications and authorizations of green invention patents as the core, improve the performance evaluation and incentive scheme for R&D personnel, raise its weight to the level equivalent to project revenue, and set step-by-step rewards. At the same time, green innovation achievements should be directly linked to professional title evaluation and post promotion, and core contributors should be given priority in project leadership. Considering the high risk of green innovation, it is necessary to establish a scientific fault tolerance mechanism, clarify boundaries, and exempt teams from liability for failures caused by uncontrollable factors such as technological exploration if they have fulfilled their obligations. A green innovation risk fund can be set up to give certain compensation to failed projects, and digital tools can be used for risk early warning and management.

Third, talent training and evaluation should focus on the cross-integration of digital and green disciplines, and build a "digital + green" integrated talent team. Special training should be carried out for existing employees, covering the application of digital technologies in environmental governance, the operation of green innovation digital tools, etc., adopting the "theory + case + practice" mode, and establishing a digital evaluation mechanism for training effects, linking the results with promotion and rewards. We can cooperate with universities to offer targeted training courses on "digital green innovation", customize teaching content, cultivate compound talents such as green data analysts and digital environmental protection engineers, establish internship bases, and give priority to hiring outstanding graduates. At the same time, we can recruit talents with both digital technology and environmental protection backgrounds from the society. In the annual excellence evaluation, a special award of "Pioneer in Digital-Green Collaboration" can be set up to give heavy rewards to individuals and teams who solve environmental problems through digitalization or improve data value through green innovation, and widely publicize the award-winning deeds to clarify the career development orientation. We should establish a "digital + green"

talent evaluation system, incorporate digital tool application ability, green innovation achievements, environmental protection contributions into the core assessment, and directly link the results with salary, promotion and training. We can also build an internal "digital + green" talent exchange platform, promote cross-departmental knowledge sharing with digital tools, establish a green knowledge database, integrate innovation achievements, operation manuals, industry practices and other content, encourage employees to upload cases and give incentives, forming a virtuous circle of "innovation-sharing-reinnovation".

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