



OPEN

## Study based on managerial compensation incentives and analyst attention perspectives of corporate digital transformation and sustainability performance

Jingjing Yao, Yun Zhang✉, Yinan Sun & Qian Bo

Based on a sample of A-share listed companies in China from 2012 to 2022, this study empirically examines the relationship between digital transformation and corporate sustainability performance. Adopting a dual perspective of internal incentives and external governance, it explores how digital transformation enhances corporate sustainability performance through executive compensation incentives and analyst attention. Regression results indicate that digital transformation improves corporate sustainability performance, with findings remaining robust after endogeneity and stability tests. Heterogeneity analysis reveals that the impact of digital transformation on sustainability performance is more pronounced in eastern regions and among non-growth-stage enterprises. These conclusions illuminate the mechanisms through which digital transformation influences sustainability performance and provide empirical evidence for promoting corporate adoption of digitalisation to enhance sustainability outcomes.

**Keywords** Digital transformation, Sustainability performance, Analyst attention, Management compensation incentives

In recent years, the world has faced mounting concerns over intensifying global climate change, escalating resource scarcity, and deepening social inequality. The United Nations'2030 Agenda for Sustainable Development has established 17 Sustainable Development Goals (SDGs), providing a comprehensive framework for global action. Concurrently, international treaties such as the Paris Agreement have mandated ambitious carbon emission reduction targets. These developments coincide with a meteoric rise in ESG investing—global assets under management utilising ESG criteria surpassed \$30 trillion in 2023—and a shift in sustainability preferences among consumers and employees. Together, these forces have fundamentally reshaped the corporate competitive environment. Against this backdrop, corporations—as major contributors to resource consumption and pollutant emissions—are facing increasingly intense scrutiny regarding their environmental responsibilities. It has become imperative for businesses to urgently incorporate sustainability into their long-term strategic planning, transcend the pursuit of short-term economic gains, and commit to a fundamental transition toward sustainable operations.

Driven by continual advancements in digital technologies—such as big data and cloud computing—China's digital economy has sustained robust growth. According to official statistics released by the National Bureau of Statistics, the scale of the digital economy exceeded 58 trillion yuan in 2023, representing 46.5% of the nation's GDP. Digital technologies—such as big data, artificial intelligence, mobile internet, and cloud computing—have emerged as critical drivers of corporate development. Enterprises are increasingly leveraging these digital tools to integrate internal resources, eliminate information silos, and optimise management processes, while actively exploring new models of value creation. Simultaneously, digitalisation enables businesses to tackle the dual challenges of maintaining economic performance and meeting environmental goals. Industry leaders such as Siemens and Toyota have demonstrated that comprehensive digital transformation can yield synergistic gains in both economic and environmental performance.

Existing research presents inconsistent conclusions regarding the relationship between digital transformation and corporate sustainability performance. Although most studies suggest a positive impact of digitalisation on

School of Finance and Economics, Jiangsu University, Zhenjiang, China. ✉email: 2212319039@stmail.ujs.edu.cn

sustainability outcomes<sup>1,2</sup>, the nature and extent of this relationship remain contested in the academic literature. However, some scholars argue that excessive or misaligned resource allocation during digital transformation could lead to heightened energy consumption and divert investments from other critical initiatives, potentially undermining long-term corporate development<sup>3</sup>. Simultaneously, digital transformation enhances economic performance by increasing operational and collaborative efficiency, integrating resources, and raising overall productivity<sup>4–6</sup>. In terms of underlying mechanisms, studies have shown that it also indirectly improves corporate sustainability performance through multiple pathways, including strengthening organisational learning and absorptive capacities<sup>7–9</sup>, promoting green technological innovation, and optimising executive team structures<sup>10</sup>.

This study examines A-share listed companies in China from 2012 to 2022. Grounded in stakeholder theory, the resource-based view, and agency theory, it investigates the mediating roles of internal incentive mechanisms and external governance mechanisms in shaping corporate sustainability outcomes, thereby contributing to the existing literature. Compared with prior studies, this research makes several key contributions. Theoretically, while existing work has largely emphasised direct effects and internal operational factors—such as improving operational efficiency or innovation capacity—or focused on moderating variables, less attention has been paid to the role of external governance mechanisms. This study explicitly analyses the mediating effects of management incentives and analyst attention in the relationship between digital transformation and corporate sustainability performance. This mechanism encourages a transition toward more sustainable development pathways by improving governance effectiveness, realigning stakeholder relationships, and fostering synergy among corporate value, capital market performance, and social benefits.

## Literature review and research hypotheses

### Digital transformation and sustainability performance

Rooted in the resource-based view, a firm's sustainable competitive advantage derives from its unique resources and capabilities. The impact of digital technology is becoming increasingly important<sup>11</sup>. Digital transformation can be conceptualised as a strategic process through which enterprises develop and reconfigure digital resources and dynamic capabilities<sup>12,13</sup>. These newly established assets are the micro-foundation for improving corporate sustainable development performance. Specifically, digital transformation enables enterprises, in the first place, to build digital resource endowments and process optimisation capabilities<sup>14,15</sup>. By restructuring production processes and organisational architectures, it reduces operational costs, improves efficiency, and enhances supply chain stability and resilience<sup>16,17</sup>—while also diminishing human error and reducing rates of waste and product returns<sup>18</sup>. Secondly, digital transformation elevates innovation capacity and capital allocation efficiency<sup>19,20</sup>, improving overall innovation performance<sup>21</sup>. Ultimately, it strengthens corporate performance by enabling novel business models—e-commerce and the sharing economy, for example—that open new revenue streams and improve financial outcomes<sup>22–24</sup>.

Furthermore, digital transformation enhances technological innovation capabilities and accelerates R&D cycles and creates broader opportunities for resource integration and market collaboration<sup>25</sup>, thereby amplifying potential value creation. In the context of environmental governance, the adoption of digital technologies facilitates the optimisation of production processes and techniques. This leads to higher energy efficiency, supports coordinated emission reduction efforts, decreases the consumption of natural resources and the discharge of pollutants, and mitigates the overall environmental footprint of corporate operations<sup>26,27</sup>. Similarly, the advancement of fintech contributes to stronger corporate governance mechanisms, proving especially impactful in managing carbon emissions<sup>28–30</sup>. Based on the above analysis, this study proposes the following hypotheses:

Hypothesis H1: Digital transformation has a positive impact on corporate sustainability performance.

### The mediating effect of management incentives

According to agency theory, the agency problems resulting from separating ownership and management in modern corporations can be alleviated through well-designed monitoring and incentive structures. Corporate digital transformation offers an effective means to enhance corporate governance by mitigating conflicts of interest and reducing information asymmetry. Furthermore, digital transformation facilitates a rational increase in executive compensation and promotes sharing digital dividends between shareholders and management<sup>31</sup>. Specifically, it enhances corporate governance by refining governance structures and strengthening managerial incentives<sup>32</sup>. At the same time, digital transformation broadens corporate financing channels, thereby alleviating financing constraints. The resulting improvement in financial flexibility allows firms to allocate capital more effectively—for instance, by implementing equity incentive plans and increasing the proportion of equity-based compensation awarded to management. Simultaneously, executive compensation incentives can serve as a driving force for corporate digital transformation, which mediates such incentives' effect on curbing real earnings management practices. However, it should be noted that poorly designed cash-based compensation systems—characterised by excessive pay levels, short-term incentive structures that encourage financial manipulation, and insufficient transparency—may undermine the intended motivational effects of compensation contracts. Therefore, digital transformation may improve corporate governance efficiency and promote sustainable development by optimising the design and implementation of executive compensation incentive mechanisms<sup>33,34</sup>. Based on the above analysis, the following hypotheses are proposed:

Hypothesis H2: Management incentives mediate the relationship between digital transformation and sustainable development performance.

According to stakeholder theory, a company's survival and development hinge on the support of its various stakeholders, with corporate governance focusing on balancing the expectations and returns of different interest groups. In this process, financial analysts serve as a critical bridge between firms and investors, fulfilling an essential role in transmitting and interpreting corporate information. Digital transformation significantly

enhances information transparency and communication efficiency<sup>35,36</sup>. Regarding information sourcing, data mining and analytics technologies unlock previously dormant information, converting unstructured and unpredictable content into transmissible, standardised digital data<sup>37,38</sup>, thereby broadening the channels of information acquisition. At the level of information dissemination, digital technologies establish more efficient pathways for the flow of information both within and outside the organisation. Thus, digital transformation fundamentally expands the scope of information companies can disclose. Public and private information constitute the complete data set accessible to analysts. As the volume of information grows, the datasets analysts utilise increasingly converge, enhancing their effectiveness in external oversight. This strengthened monitoring function further incentivises firms to mitigate risks, enhance reputational capital, achieve legitimacy, and create shared value<sup>39</sup>. Consequently, while maintaining economic performance, companies are driven to evolve into socially recognised, environmentally responsible, and sustainable organisations<sup>40</sup>. Given the above, we propose the following hypothesis:

Hypothesis H3: Analyst attention mediates the relationship between digital transformation and sustainable development performance.

Based on the analysis provided, we propose the conceptual framework for this paper, illustrated in Fig. 1. In this framework, digital transformation is identified as the core independent variable, while corporate sustainable development performance is the dependent variable. Additionally, analyst attention and executive compensation incentives act as mediating variables.

## Methodology

### Samples and data collection

We adopted the panel data of A-share listed companies covering 2012–2022 as the research sample for this study. To ensure the data's objectivity, completeness, and validity, we implemented the following data processing procedures: First, we excluded sample companies with abnormal trading status (i.e., ST- and \*ST-designated companies). Second, we removed samples of companies in the financial sector. Third, we excluded samples with severe data missingness. Through this process, we obtained 26,085 valid observations. We sourced data on environmental performance from the Huazheng ESG Rating System, whereas we retrieved other data from the China Social Science Management Research Database (CSMAR). Additionally, we winsorized all continuous variables at the 1% and 99% levels to mitigate the potential impact of extreme values.

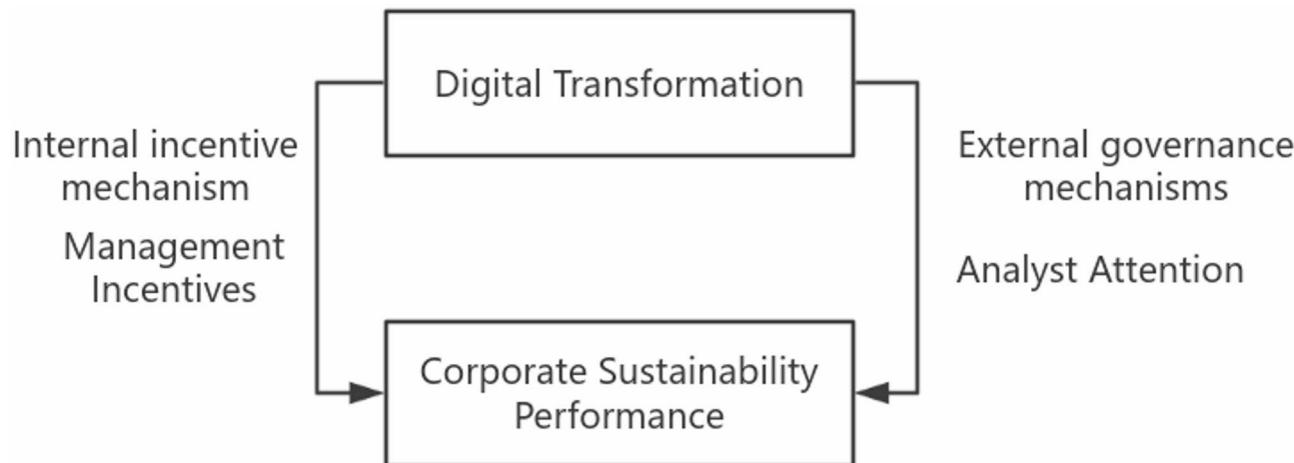
### Variable measures

#### Dependent variable

Corporate sustainability performance must encompass both economic viability and environmental sustainability, with their level of synergy directly reflecting an enterprise's capacity for sustainable development. The long-term stability of return on assets (ROA) is highly correlated with a company's sustainability capability. The environmental score in Huazheng ESG incorporates quantitative metrics such as greenhouse gas emissions, carbon neutrality pathways, water consumption, waste discharge, and renewable energy usage. It employs a combined positive and negative assessment approach, with negative indicators including industrial emissions, electronic waste, and environmental penalties, providing a comprehensive reflection of corporate environmental performance. Furthermore, the entropy weighting method aligns with the rigorous measurement requirements for sustainability performance. Therefore, the environmental score from Huazheng ESG and the entropy weight of a company's return on assets (ROA) are selected as proxy indicators for sustainability.

#### Independent variable

The China Stock Market & Accounting Research Database (CSMAR) employs precise numerical metrics across three dimensions—organisational empowerment, environmental support, and digital outcomes—to measure



**Fig. 1.** Conceptual framework of the research.

corporate digital transformation. This approach reduces the impact of discrepancies between annual reports and actual practices on experimental results, offering greater objectivity than existing text analysis methods. This paper utilises the digital transformation index within the database to assess corporate digital transformation. The specific measurement methodology is as follows: Enterprise digital transformation index = 0.3472×strategy-driven score + 0.162×technology-enabled score + 0.0969×organizational-enabled score + 0.0342×environmental-enabled score + 0.2713×digital outcome score + 0.0884×digital application score.

Mediating variable. This study selects compensation incentives, specifically taking the logarithm of management compensation. Higher values indicate more substantial compensation incentives for management.

Mediating variable. This study uses the number of securities analysts tracking a listed company to measure analyst attention. The natural logarithm of the number of teams issuing earnings forecasts for a listed company in each fiscal year, plus one, serves as a proxy variable for analyst attention.

Control variables. In this paper, we have chosen the following control variables for the experiment: firm size(Size), debt-to-equity ratio(Lev), revenue growth rate(Growth), proportion of independent directors(Indep), cash flow ratio(Cashflow), dual-role positions (Dual), firm value(TobinQ), listing tenure(ListAge), audit quality(Big4), and audit opinion(Opinion). Additionally, based on the results of the Hausman test, we employed a fixed-effects model, treating both industry and year as fixed effects.g both industry and year as fixed effects. as fixed effects.

The variables are defined as shown in Table 1.

### Model setting

In comparison with the structural equation model, regression analysis is better suited to investigating the specific operational mechanisms within a model. Numerous studies focusing on regression analysis as an empirical approach have been published in mainstream academic journals across the globe. Thus, regression analysis is selected as the empirical method for the present study. Drawing on the theoretical analysis conducted earlier, the following models are estimated to test the research hypotheses put forward above:

First, to verify hypothesis H1, we constructed a regression model examining the relationship between digital transformation and sustainable development performance (1).

$$Dtp_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_2 Controls + \sum Year + \sum Industry + \epsilon_{it} \quad (1)$$

In Model (1), the subscript i represents firms, and the subscript t represents years. Model (1) employs ordinary least squares regression with fixed effects for year and industry. We control for the effects of time and industry variations on sustainability performance.

Second, to test Hypothesis H2, this study employs managerial compensation incentives (Salary) as the mediating variable. The specific model is as follows(2)¶3‡:

$$Salary_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_2 Controls + \sum Year + \sum Industry + \epsilon_{it} \quad (2)$$

$$Dtp_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 Salary + \gamma_3 Controls + \sum Year + \sum Industry + \epsilon_{it} \quad (3)$$

Finally, to test hypothesis H3, this paper constructs model (4)(5) with analyst attention as the mediating variable.

Variable type	Variable symbol	Definition and description
Dependent variable	Dtp	ROA and Score entropy weights sum
Independent variable	Dig	Digital Transformation Index
Mediating variable	Salary	Natural logarithm of total management compensation
Mediating variable	Analyst	Analysts' focus on the natural logarithm
Control variables	Size	Natural logarithm of total assets at the end of the period
	Lev	Ratio of total liabilities to total assets
	Growth	Ratio of operating revenue growth to total operating revenue of the previous year
	Indep	Ratio of Independent Directors to Total Board Members
	Cashflow	Ratio of Net Cash Flow from Operating Activities to Current Liabilities at the End of the Period
	Dual	The chairman and general manager are assigned a value of 1 for the same person; otherwise, it is 0.
	TobinQ	Market value of the firm/replacement cost of the firm's assets
	ListAge	Natural logarithm of the listing duration
	Big4	1 if audited by a Big 4 audit firm, 0 otherwise
	Opinion	Standard audit opinion takes the value of 1, others 0
	Year	Annual dummy variable
	Industry	Industry dummy variable

**Table 1.** Definition and description of control variables.

$$Analyst_{it} = \delta_0 + \delta_1 Digi_{it} + \delta_2 Controls + \sum Year + \sum Industry + \epsilon_{it} \quad (4)$$

$$Dtp_{it} = \eta_0 + \eta_1 Digi_{it} + \eta_2 Analyst + \eta_3 Controls + \sum Year + \sum Industry + \epsilon_{it} \quad (5)$$

## Empirical results and discussion

### Descriptive statistics

Table 2 displays the results of the descriptive statistics analysis. The mean value of Dtp slightly exceeds the median, indicating a mild right skew in the distribution. This suggests that most firms perform near the average in terms of sustainability. In contrast, the mean value of Dig is below the median, and the distribution also shows a mild right skew, which may indicate that most firms are excelling in digital transformation. There are significant variations in digitisation levels among firms, likely due to differences in the regions and industries in which they operate. The mean value of Analyst Focus is greater than the median, again showing a slight right skew. Meanwhile, the mean value of Salary is close to the median, suggesting that management compensation is relatively evenly distributed among the sample firms. Additionally, there are fewer firms with dual powers than those with separate powers, reflecting the current trend in corporate governance structures. The debt levels of most firms remain within a reasonable range, and the growth data exhibit a normal distribution, indicating a stable growth trend across firms. In auditing, only a small number of firms are audited by the Big Four accounting firms, while the majority receive a standard unqualified audit opinion.

### Regression analysis

#### Basic result

Table 4 presents the results of the primary regression analysis, which examines the relationship between digital transformation and sustainability performance. The findings indicate that larger firm size and greater cash flow are associated with improved sustainability performance. Specifically, the coefficient for digital transformation is 0.001, which is statistically significant at the 1% level ( $p < 0.01$ ). For each one standard deviation increase in digital transformation level, a firm's sustainable development performance is expected to rise by about 8% within its variability range. This indicates that digital transformation has a positive impact on sustainability performance, thereby validating hypothesis H1. Additionally, the variance inflation factor (VIF) for all variables is below 10, suggesting that multicollinearity is not a significant issue in the model. These results emphasise that digital transformation can significantly enhance corporate sustainability performance.

#### Mediating effect analysis

The mediating effect was assessed through stepwise regression, focusing on the role of salary in Models 1, 2, and 3. As shown in the table, the coefficient for Dig in Model 1, the coefficient for Dig in Model 2, and the coefficient for salary in Model 3 were all significant at the 1% level. This finding indicates that salary mediates the relationship between Dig and Dtp. In Model 3, the Dig coefficient remains significant at the 1% level, indicating

Variables	N	Mean	SD	Min	Median	Max
Dtp	26,085	0.4610	0.105	0.23	0.46	0.77
Dig	26,085	36.4584	9.958	23.08	34.44	64.70
Analyst	26,085	1.3182	1.160	0.00	1.10	3.78
Salary	26,085	15.0311	0.711	13.17	15.00	17.15
Size	26,085	22.2080	1.180	20.00	22.04	26.07
Lev	26,085	0.4137	0.193	0.06	0.41	0.87
Cashflow	26,085	0.0489	0.061	-0.14	0.05	0.23
Growth	26,085	0.1412	0.298	-0.51	0.10	1.82
Indep	26,085	37.6085	5.266	33.33	36.36	57.14
Dual	26,085	0.2922	0.455	0.00	0.00	1.00
TobinQ	26,085	1.9471	1.059	0.85	1.61	7.67
ListAge	26,085	2.1161	0.822	0.00	2.20	3.37
Big4	26,085	0.0526	0.223	0.00	0.00	1.00
Opinion	26,085	0.9791	0.143	0.00	1.00	1.00

**Table 2.** Descriptive statistics of variables. **Correlation analysis.** Table 3 presents an in-depth analysis of the correlations among variables. The results demonstrate a statistically significant positive correlation between Dtp and dig at the 1% significance level. This finding suggests that digital transformation exerts a substantial positive effect on enhancing sustainability performance, thus offering preliminary support for hypothesis H1. Furthermore, the analysis reveals that both analysts' attention and management compensation incentives exhibit a statistically significant positive correlation with digital transformation and sustainability performance, respectively, at the 1% significance level. These results underscore the critical role of digital transformation in improving sustainability performance, highlighting the positive influence of analysts' attention and management compensation incentives in this mechanism.

Variables	Dtp	Dig	Analyst	Salary	Size	Lev	Cashflow
Dtp	1						
Dig	0.059***	1					
Analyst	0.057***	0.065***	1				
Salary	0.117***	0.137***	0.280***	1			
Size	0.202***	0.024***	0.338***	0.421***	1		
Lev	0.103***	-0.042***	-0.012*	0.120***	0.525***	1	
Cashflow	0.031***	-0.074***	0.188***	0.127***	0.055***	-0.146***	1
Growth	-0.019***	0.024***	0.184***	0.060***	0.030***	0.024***	0.021***
Indep	-0.0100	0.062***	-0.012**	-0.048***	-0.030***	-0.021***	-0.013**
Dual	-0.047***	0.070***	0.017***	-0.00600	-0.196***	-0.135***	-0.013**
TobinQ	-0.132***	0.094***	0.143***	-0.062***	-0.386***	-0.308***	0.099***
ListAge	0.056***	0.044***	-0.076***	0.080***	0.444***	0.342***	-0.00500
Big4	0.058***	-0.028***	0.126***	0.199***	0.283***	0.086***	0.060***
Opinion	0.016***	0.00300	0.087***	0.049***	0.019***	-0.079***	0.052***
Variables	Growth	Indep	Dual	TobinQ	ListAge	Big4	Opinion
Growth	1						
Indep	-0.00200	1					
Dual	0.042***	0.116***	1				
TobinQ	0.091***	0.036***	0.087***	1			
ListAge	-0.115***	-0.038***	-0.253***	-0.080***	1		
Big4	-0.012*	0.013**	-0.058***	-0.071***	0.060***	1	
Opinion	0.066***	0.00800	0.00100	0.00600	-0.061***	0.016***	1

**Table 3.** Correlation analysis of variables. \*\*\*, \*\* and \* respectively indicate that the parameter Estimation is significant at 0.01, 0.05 and 0.1.

a direct effect between Dig and Dtp, with wages partially mediating this relationship. Furthermore, based on the regression coefficients from each model, the indirect effect of wages is 0.00001218 ( $\beta_1\gamma_2$ ), whose positive sign aligns with the 0.0006 direct effect. This result confirms that compensation partially mediates the indirect effect of digitalization on corporate value, accounting for 12.18% of the total effect ( $\beta_1\gamma_2\alpha_1$ ). Essentially, digital transformation optimizes performance measurement systems, enabling the design of more efficient executive compensation schemes. This synergistic effect between managerial incentives and digital transformation ultimately enhances the company's sustainable development performance. Therefore, H2 is verified.

The mediating effect of Analyst was tested through Models 1, 4, and 5. The coefficients for Dig in Models 1 and 4, as well as the coefficient for Analyst in Model 5, were all significant (at the 1%, 1%, and 5% levels, respectively) in Table 4, indicating that Analyst also mediated this relationship. The coefficient for Dig remained significant in Model 5, confirming its partial mediating effect. The indirect effect mediated by Analyst is 0.0000144 ( $\delta_1\eta_2$ ), accounting for 14.4% of the total effect ( $\delta_1\eta_2\alpha_1$ ). Digital transformation attracts greater analyst attention by generating more structured data and reducing information acquisition costs. Analysts then function as an external governance mechanism, mitigating information asymmetry and easing financing constraints, ultimately enhancing corporate sustainability performance. Therefore, H3 is verified.

### Robustness tests

#### Instrumental variables method

This study uses the digital transformation index from the previous period as an instrumental variable and applies two-stage least squares (2SLS) to analyse sustainable development performance. Considering the inherent lag effect in corporate digital transformation, the impact of lagged digital transformation levels on current outcomes validates the instrument. As shown in Column (2) of Table 5, during the first-stage regression, the coefficient for the lagged digital index concerning Dig is significantly positive at the 1% significance level. In the second-stage regression (Column 3), the coefficient of the digital transformation index on sustainability performance is also significantly positive at the 1% significance level. This suggests that, after addressing endogeneity issues, the positive effect of digital transformation on sustainability performance remains strong and consistent.

#### Propensity score matching method

First, we divided the sample enterprises into two groups based on their level of digital transformation: a high digital transformation group (treatment group) and a low digital transformation group (control group), using the median level of digital transformation as the cutoff point. Next, all control variables were included as covariates, and we employed a 1:1 nearest neighbour matching approach with replacement, utilising a Logit model for the matching process. Finally, regression analysis was conducted using the matched samples. Column (4) of Table 5 results indicate a significantly positive correlation coefficient at the 1% significance level. This confirms that our research findings are robust, even after addressing endogeneity issues, and demonstrates that digital transformation significantly enhances corporate sustainable development performance.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
	Dtp	Salary	Dtp	Analyst	Dtp
Dig	0.001*** (7.12)	0.0042*** (8.31)	0.0006*** (6.97)	0.0096*** (12.46)	0.0006*** (6.94)
Salary			0.0029*** (2.82)		
Analyst					0.0015** (2.16)
Size	0.020*** (25.82)	0.3285*** (72.38)	0.0186*** (22.41)	0.7021*** (101.97)	0.0186*** (20.68)
Lev	0.009** (2.25)	-0.2033*** (-8.47)	0.0096** (2.40)	-0.9469*** (-26.01)	0.0104** (2.57)
Cashflow	0.038*** (3.66)	0.9750*** (15.62)	0.0353*** (3.37)	1.9304*** (20.38)	0.0353*** (3.36)
Growth	-0.011*** (-5.05)	0.0359*** (2.86)	-0.0107*** (-5.10)	0.4056*** (21.28)	-0.0112*** (-5.29)
Indep	-0.000*** (-2.26)	-0.0093*** (-13.40)	-0.0002** (-2.02)	-0.0026** (-2.50)	-0.0003** (-2.23)
Dual	-0.007*** (-4.91)	0.0390*** (4.68)	-0.0069*** (-4.99)	0.1151*** (9.11)	-0.0070*** (-5.02)
TobinQ	-0.005*** (-6.52)	0.0657*** (15.90)	-0.0047*** (-6.77)	0.3466*** (55.24)	-0.0050*** (-6.87)
ListAge	-0.004*** (-4.15)	-0.1011*** (-18.71)	-0.0035*** (-3.80)	-0.3598*** (-43.89)	-0.0032*** (-3.44)
Big4	0.005* (1.73)	0.2278*** (13.38)	0.0043 (1.49)	-0.0816*** (-3.16)	0.0050* (1.77)
Opinion	0.008* (1.93)	0.1197*** (4.72)	0.0078* (1.85)	0.2219*** (5.76)	0.0079* (1.85)
Constant	0.071*** (4.08)	7.4976*** (71.91)	0.0491** (2.57)	-13.6544*** (-86.31)	0.0912*** (4.61)
N	26,085	26,085	26,085	26,085	26,085
R-squared	0.150	0.341	0.151	0.431	0.150
Year	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES

**Table 4.** Digital transformation and corporate sustainability Performance. \*\*\*, \*\*, and \* respectively indicate that the parameter Estimation is significant at 0.01, 0.05, and 0.1. The “t” value is in parentheses.

#### Leading and lagging explanatory variables

To ensure the robustness of the research findings, this study assessed the digital transformation index for both preceding and lagging periods, with the results shown in Table 6 (Columns 2 and 3). Whether the digital transformation index was measured one period ahead or one period behind, the correlation coefficients remained statistically significant at the 1% level. This confirms the model's robustness and the reliability of its primary conclusions.

#### Substituting variables

To further validate the robustness of the research findings, this paper employs the substitute variable method to redefine the dependent variable, Dtp. Specifically, the environmental score from the Bloomberg ESG database is chosen as the metric for environmental performance. We constructed Dtp using return on assets (ROA) and environmental performance (ENVI). The formula used is as follows<sup>41</sup>:  $Dtp = [(1?|ROA?ENVI|) \times \sqrt{ROA \times ENVI}] / 1$ . Table 6 (Column 4) shows that all correlation coefficients are significantly positive at the 1% level. This finding further supports the credibility of the paper's main conclusions, demonstrating that the positive impact of digital transformation on corporate sustainable development performance is indeed robust.

#### Heterogeneity analysis

##### Regional heterogeneity of enterprises

The analysis results are shown in Table 7, where columns (2), (3), and (4) present the empirical analysis results for each region, respectively. In the regional grouping analysis, the digitalisation coefficient for the eastern region is significant at the 1% significance level. In comparison, the coefficients for the central and western areas are essential at the 5% significance level. This finding indicates that although digital transformation demonstrates

Variables	First phase	Second phase	Model 1
	Dig	Dtp	Dtp
L.Dig	0.8838*** (260.19)		
Treat_Dig			0.0076*** (5.16)
Dig		0.0006*** (5.51)	
Size	0.2667*** (8.69)	0.0196*** (22.36)	0.0194*** (26.02)
Lev	-0.1870 (-1.15)	0.0081* (1.74)	0.0066 (1.63)
Cashflow	0.2892 (0.67)	0.0430*** (3.54)	0.0508*** (4.90)
Growth	0.4499*** (5.20)	-0.0098*** (-4.00)	-0.0109*** (-5.31)
Indep	0.0034 (0.73)	-0.0002 (-1.33)	-0.0003** (-2.32)
Dual	0.1037* (1.85)	-0.0082*** (-5.14)	-0.0065*** (-4.67)
TobinQ	0.0337 (1.18)	-0.0047*** (-5.73)	-0.0065*** (-10.05)
ListAge	-0.0315 (-0.75)	-0.0070*** (-5.89)	-0.0020** (-2.23)
Big4	-0.1587 (-1.39)	0.0041 (1.25)	0.0102*** (3.34)
Opinion	0.6057*** (3.62)	0.0052 (1.09)	0.0054 (1.29)
Constant	-1.9229*** (-2.72)	0.0901*** (4.49)	0.0969*** (5.71)
N	20,165	20,165	26,083
R-squared		0.140	0.148
Year	YES	YES	YES
Industry	YES	YES	YES

**Table 5.** Robustness test—Instrumental variables method and propensity score matching method. \*\*\*, \*\*, and \* respectively indicate that the parameter Estimation is significant at 0.01, 0.05, and 0.1. The “t” value is in parentheses.

substantial effects across all regions, its impact on enhancing corporate sustainable development performance is more pronounced in the eastern region compared to the central and western areas. From the perspective of institutional theory and complementary assets, the East region benefits from a superior institutional environment and resource endowments. This allows it to maximise the advantages of digital technologies more effectively. Enterprises in the eastern region are more likely to achieve data interconnectivity, enhancing these technologies' network and scale effects. In contrast, the central and western areas encounter challenges related to market mechanisms, resource availability, and environmental conditions, which limit their ability to fully reap the benefits of digital transformation on corporate sustainable development performance.

#### *Heterogeneity in the Corporate life cycle*

From the perspective of the corporate life cycle stage (Columns 5 to 7), the effects of digital transformation are most potent in mature (Coefficient = 0.0005, t = 3.38) and declining (Coefficient = 0.0008, t = 6.05) enterprises, exhibiting high significance at the 1% level. In contrast, these effects are insignificant in growing enterprises (Coefficient = 0.0001, t = 0.48). Considering firms' core demands and resource constraints at different lifecycle stages. Mature firms typically possess stable cash flows and robust resource bases, enabling them to support large-scale digital investments and withstand transformation risks, thus achieving the most pronounced value enhancement effects. Firms in the decline stage face survival pressures and strategic repositioning, where digital transformation yields higher sustainable development performance. Conversely, growth-stage firms encounter resource constraints that may result in less significant returns on digital investments.

	Model 1	Model 1	Model 1
Variables	Dtp	Dtp	Dtp
L.Dig	0.0005*** (5.50)		
F.Dig		0.0006*** (6.14)	
Dig			0.0005*** (3.96)
Size	0.0197*** (22.63)	0.0192*** (21.15)	0.0239*** (21.19)
Lev	0.0079* (1.72)	0.0156*** (3.27)	-0.0259*** (-3.80)
Cashflow	0.0432*** (3.54)	0.0393*** (3.17)	0.0540*** (3.21)
Growth	-0.0096*** (-3.88)	-0.0120*** (-4.83)	-0.0027 (-0.77)
Indep	-0.0002 (-1.31)	-0.0004*** (-2.84)	-0.0000 (-0.23)
Dual	-0.0081*** (-5.10)	-0.0078*** (-4.80)	-0.0029 (-1.18)
TobinQ	-0.0046*** (-5.70)	-0.0058*** (-6.84)	-0.0006 (-0.58)
ListAge	-0.0070*** (-5.89)	-0.0031*** (-2.95)	-0.0072*** (-4.40)
Big4	0.0040 (1.22)	0.0000 (0.00)	0.0452*** (14.41)
Opinion	0.0055 (1.16)	0.0004 (0.08)	0.0072 (1.01)
Constant	0.0890*** (4.43)	0.0978*** (4.68)	-0.4963*** (-18.54)
N	20,165	20,165	9,467
R-squared	0.140	0.153	0.349
Year	YES	YES	YES
Industry	YES	YES	YES

**Table 6.** Robustness test—Leading and lagging explanatory variables and substituting variables. \*\*\*, \*\*, and \* respectively indicate that the parameter Estimation is significant at 0.01, 0.05, and 0.1. The “t” value is in parentheses.

## Discussion

Unlike the research by Li et al.<sup>42</sup>, this study finds that digital transformation can effectively enhance corporate sustainability performance. The findings indicate that digital transformation exerts both internal motivational and external oversight effects by increasing management compensation incentives and analyst attention, respectively. These conclusions remain valid after robustness tests employing proxy variables and propensity score matching methods.

Specifically, building on the examination of the digital transformation-sustainability performance relationship, this study proposes two mediating variables. While existing research has focused mainly on analysing moderation effects, exploration of mediating mechanisms remains relatively scarce. digital transformation helps align management interests with non-financial objectives, incentivising greater resource allocation to sustainability initiatives. Concurrently, it significantly enhances corporate transparency, attracting increased analyst scrutiny. Leveraging analysts' information interpretation and market oversight functions, this heightened attention drives corporate improvements in sustainability practices. The findings indicate that digital transformation can enhance corporate sustainability performance through these two pathways. Furthermore, policies encourage enterprises to adopt new technologies such as artificial intelligence and industrial internet for intelligent upgrades and digital transformation (“Smart Upgrades and Digital Transformation”), while simultaneously promoting green initiatives like energy conservation, carbon reduction, and green manufacturing—as seen in regions like Henan and Anhui. Policies promote the sustainable development of the macroeconomy<sup>43</sup>. These measures significantly advance sustainability performance. Enterprises should seize this policy window to pursue digital transformation, enhancing sustainable development outcomes.

Variables	East	West	Central	Growth	Maturity	Recession
Dig	0.0006*** (5.74)	0.0005** (2.39)	0.0006** (2.31)	0.0001 (0.48)	0.0005*** (3.38)	0.0008*** (6.05)
Size	0.0187*** (20.59)	0.0165*** (8.27)	0.0249*** (12.95)	0.0187*** (9.73)	0.0178*** (14.10)	0.0218*** (18.81)
Lev	0.0129*** (2.68)	0.0093 (0.90)	-0.0148 (-1.42)	0.0090 (0.86)	0.0128* (1.84)	0.0042 (0.72)
Cashflow	0.0427*** (3.44)	0.0267 (1.03)	0.0327 (1.17)	-0.0073 (-0.30)	0.0137 (0.79)	0.0812*** (5.05)
Growth	-0.0109*** (-4.37)	-0.0132** (-2.38)	-0.0060 (-1.17)	-0.0119*** (-2.66)	-0.0146*** (-3.92)	-0.0008 (-0.17)
Indep	-0.0003** (-2.09)	0.0001 (0.47)	-0.0005 (-1.59)	-0.0005* (-1.74)	-0.0001 (-0.58)	-0.0003 (-1.49)
Dual	-0.0077*** (-4.77)	-0.0002 (-0.05)	-0.0018 (-0.43)	0.0008 (0.26)	-0.0085*** (-3.70)	-0.0088*** (-4.11)
TobinQ	-0.0058*** (-7.03)	-0.0043** (-2.43)	0.0016 (0.85)	-0.0040*** (-2.69)	-0.0054*** (-4.69)	-0.0037*** (-3.18)
ListAge	-0.0015 (-1.41)	-0.0026 (-1.12)	-0.0098*** (-4.24)	0.0058** (2.45)	-0.0023 (-1.44)	-0.0080*** (-5.47)
Big4	-0.0032 (-0.96)	0.0317*** (4.15)	0.0118 (1.37)	-0.0029 (-0.40)	0.0082* (1.68)	0.0055 (1.36)
Opinion	0.0088* (1.70)	0.0150 (1.35)	0.0063 (0.65)	0.0152 (1.06)	0.0142* (1.71)	0.0006 (0.11)
Constant	0.0923*** (4.34)	0.1078** (2.42)	-0.0175 (-0.40)	0.0860* (1.93)	0.0955*** (3.23)	0.0395 (1.50)
N	18,641	4,081	3,359	4,409	9,265	12,007
R-squared	0.144	0.198	0.268	0.174	0.150	0.158
Year	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES

**Table 7.** Heterogeneity Analysis. \*\*\*, \*\* and \* respectively indicate that the parameter Estimation is significant at 0.01, 0.05 and 0.1. The “t” value is in parentheses.

## Conclusions and implications

### Conclusions

This study, which is based on the resource-based view, stakeholder theory, and institutional theory, investigates how digital transformation impacts corporate sustainability performance, using a sample of Chinese listed companies. It examines both empirical and theoretical aspects while testing relevant mediating effects. The findings suggest that digital transformation improves corporate sustainability performance by enhancing managerial incentives. Additionally, it can influence external governance through analyst attention. Analysts' attention and managerial incentives significantly mediate between digital transformation and corporate sustainability performance.

### Management implications

#### *From the corporate level*

We need to tailor strategies to the stage of development. Growing enterprises should plan a digital approach to expand their market presence rapidly; mature companies must leverage digitalisation to optimise processes and consolidate competitive advantages; declining businesses must explore digital models to pursue business transformation and identify new growth opportunities, fostering sustainable development.

Enterprises should effectively coordinate the internal drivers of management with the external governance role of analysts. Management must build and enhance dynamic capabilities to seize strategic opportunities arising from digital transformation more effectively. Simultaneously, digital transformation can be a key pathway to improve corporate information transparency. Analysts, in turn, should leverage digital technologies to deepen their interpretation and integration of corporate information, thereby conveying insights more efficiently and accurately to relevant market decision-makers. This will ultimately promote sustainable corporate development.

#### *From the government level*

The government should strengthen incentives and support for enterprises' digital transformation by improving the regulatory environment and providing financial subsidies or policy incentives. This facilitates the maximization of benefits derived from digital transformation initiatives.

## Limitations and future research

Although this paper examines the mechanisms linking digital transformation and sustainability performance from internal and external perspectives, several limitations remain. First, the research sample is restricted to Chinese A-share listed companies, limiting the scope and temporal relevance of the findings, which may not apply to other enterprises. Second, focusing solely on internal drivers and external governance mechanisms may fail to capture the breadth of sustainability performance fully. Finally, the quantitative metrics used to assess digital transformation and sustainability performance may not fully capture their complexity and multidimensional characteristics. Therefore, future research requires more comprehensive and innovative variables to measure digital transformation and corporate sustainability performance.

## Data availability

The data supporting the conclusions of this study are all derived from the China Stock Market & Accounting Research (CSMAR) database, and these data can be obtained by making a reasonable request to the corresponding author.

Received: 14 July 2025; Accepted: 19 September 2025

Published online: 24 October 2025

## References

1. Di, A. & Varriale, L. Blockchain technology in supply chain management for sustainable performance: evidence from the airport industry. *Int. J. Inf. Manag.* **52**, 102014. <https://doi.org/10.1016/j.ijinfomgt.2019.09.010> (2020).
2. Zhou, Z., Yuan, Z. & He, C. Can digital transformation promote firms' sustainable development? Evidence based on ESG performance. *Int. Rev. Financ. Anal.* (2025) **105** 104434. <https://doi.org/10.1016/j.irfa.2025.104434>.
3. Ahmadova, G., Delgado-Márquez, B. L. & Pedauga, L. E. Leyva-de La Hiz, D. I. Too good to be true: the inverted U-shaped relationship between home-country digitalization and environmental performance. *196* 107393. <https://doi.org/10.1016/j.ecolecon.2022.107393> (2022). *Ecol. Econ.*
4. Xu, Q., Li, X. & Guo, F. Digital transformation and environmental performance: evidence from Chinese resource-based enterprises. *Corp. Soc. Responsib. Environ. Manag.* **30**, 1816–1840. (2023). <https://doi.org/10.1002/csr.2457>
5. Li, T., Li, Q. & Chen, C. X. The effect of data management ability on firm Productivity—New evidence from China Employer-Employee survey. *China Ind. Econ.* (2020), 174–192. <https://doi.org/10.19581/j.cnki.ciejournal.2020.06.010>.
6. Cui, Y. X., Zhao, C. Y. & Zhang, Q. Impact of digital transformation in agribusinesses on total factor productivity. *Int. Food Agribus Manag Rev.* **27** (5), 843–857. <https://doi.org/10.22434/IFAMR1064> (2024).
7. Zhang, S., Ge, J. & Li, Y. How legacy firms achieve digital transformation through brand flagship platform: the role of digital platform capability. *J. Bus. Ind. Mark.* **40**, 1507–1524. <https://doi.org/10.1108/JBIM-08-2024-0586> (2025).
8. Ansari, I., Barati, M., Sadeghi Moghadam, M. R., Ghobakhloo, M. & Empowering Industry 4.0: systemizing readiness assessment and strategic roadmapping for digital transformation. *J. Manuf. Technol. Manag.* **36**(5), 937–960. (2025). <https://doi.org/10.1108/JMTM-05-2024-0257>
9. Cornish, G. et al. Intermediation and digitalisation in sustainability transitions: a case report from the Australian agrifood sector. *Sustain. Sci.* (2025). <https://doi.org/10.1007/s11625-025-01733-4>
10. Shao, L., Gong, J., Fan, W., Zhang, Z. & Zhang, M. Cost comparison between digital management and traditional management of cotton fields—Evidence from cotton fields in Xinjiang, China. *Agric* **12** (8), 1105. <https://doi.org/10.3390/agriculture12081105> (2022).
11. Zhang, R., Zhu, H., Chang, Q. & Mao, Q. A comprehensive review of digital twins technology in agriculture. *Agric* **15** (9), 903. <https://doi.org/10.3390/agriculture15090903> (2025).
12. Lin, Y. & Wu, L. Y. Exploring the role of dynamic capabilities in firm performance under the resource-based view framework. *J. Bus. Res.* (2014), 407–413. <https://doi.org/10.1016/j.jbusres.2012.12.019>
13. Lu, S., Sun, Z. & Huang, M. The impact of digital literacy on farmers' pro-environmental behavior: an analysis with the theory of planned behavior. *Front. Sustain. Food Syst.* **8**. <https://doi.org/10.3389/fsufs.2024.1432184> (2024).
14. Jiang, W. & Wang, X. Enterprise digital transformation empowers supply chain stability. *Financ. Res. Lett.* **66**, 105693. (2024). <https://doi.org/10.1016/j.frl.2024.105693>
15. Gong, Y., Yang, J. & Shi, X. Towards a comprehensive Understanding of digital transformation in government: analysis of flexibility and enterprise architecture. *Gov. Inf. Q.* **37**, 101487. <https://doi.org/10.1016/j.giq.2020.101487> (2020).
16. Qi, R., Ma, G., Liu, C., Zhang, Q. & Wang, Q. Enterprise digital transformation and supply chain resilience. *Financ Res. Lett.* **66**, 105564. <https://doi.org/10.1016/j.frl.2024.105564> (2024).
17. Karttunen, E., Lintukangas, K. & Hallikas, J. Digital transformation of the purchasing and supply management process. *Int. J. Phys. Distrib. Logist. Manag.* **53**(5–6), 685–706. (2023). <https://doi.org/10.1108/IJPDLM-06-2022-0199>
18. Yin, X. N., Zhan, X. M. & Tang, S. Q. The impact mechanism of manufacturing enterprises' digital transformation on financial performance. *China Bus. Mark.* **36** (7), 96–106. <https://doi.org/10.14089/j.cnki.cn11-3664/f.2022.07.009> (2022).
19. Peng, Y. & Tao, C. Can digital transformation promote enterprise performance? —From the perspective of public policy and innovation. *J. Innov. Knowl.* **7** (3), 100198. <https://doi.org/10.1016/j.jik.2022.100198> (2022).
20. Wang, Q., Huang, H. & Liu, T. Job destruction or job creation? Evidence from carbon emission trading policies. *Econ. Anal.* (2024). 1010–1028. <https://doi.org/10.1016/j.eap.2024.10.017>
21. Wang, Y. & He, P. Enterprise digital transformation, financial information disclosure and innovation efficiency. *Financ Res. Lett.* **59**, 104707. <https://doi.org/10.1016/j.frl.2023.104707> (2024).
22. Durnoi, A., Teodorescu, C., Vargas, V. & Ioanăs, C. Analysing EU countries' digital progress towards sustainable development goals. *Amfit Econ.* **25**, 987. <https://doi.org/10.24818/EA/2023/S17/987> (2023).
23. Chi, R. Y., Zheng, R. Y. & Ruan, H. P. Double changes of manufacturing and business model in the digital transformation of enterprises. *Sci. Stud.* **40** (1), 172–181. <https://doi.org/10.16192/j.cnki.1003-2053.20210412.001> (2022).
24. Teece, D. J. Profiting from innovation in the digital economy: enabling technologies, standards, and licensing models in the wireless world. *Res. Policy.* (8), 1367–1387. <https://doi.org/10.1016/j.respol.2017.01.015> (2018). 47.
25. Zou, S., Fan, X., Zhou, Y. & Cui, Y. Achieving collaborative pollutant and carbon emissions reduction through digital governance: evidence from Chinese enterprises. *Environ. Res.* **263** (3), 120197. <https://doi.org/10.1016/j.envres.2024.120197> (2024).
26. Wei, Z. & Sun, L. How to leverage manufacturing digitalisation for green process innovation: an information processing perspective. *Ind. Manag Data Syst.* **121**(5), 1026–1044. <https://doi.org/10.1108/IMDS-08-2020-0459> (2021).
27. Nayal, K., Raut, R. D., Yadav, V. S., Priyadarshinee, P. & Narkhede, B. E. The impact of sustainable development strategy on sustainable supply chain firm performance in the digital transformation era. *Bus. Strat. Env.* **33**, 4974–4975. <https://doi.org/10.1002/bse.3783> (2024).

28. Dhiab, M. M., Khakan, N., Atayah, O. F., Marashdeh, H. & El Khoury, R. The role of fintech for manufacturing efficiency and financial performance: in the era of industry 4.0. *J. Decis. Syst.* **33** (2), 220–241. <https://doi.org/10.1080/12460125.2022.2094527> (2022).
29. Najaf, K. et al. Fintech and corporate governance: in times of financial crisis. *Electron.* 605–628. <https://doi.org/10.1007/s10660-023-09733-1> (2024).
30. Najaf, K. et al. The impact of carbon emissions on market performance: fintech versus non-fintech. *Electron. Commer. Res.* (2024). <https://doi.org/10.1007/s10660-024-09866-x>
31. Jin, X. K., Xu, L. P., Xin, Y. & Teng, F. Digital transformation and executive pay-performance sensitivity. *World Econ.* **48** (4), 170–196. <https://doi.org/10.19985/j.cnki.cassjwe.2025.04.013> (2025).
32. Chen, D., Zhang, Q., Enterprise digital transformation and management incentives. *Econ. Manag.* **45** (5), 132–150. <https://doi.org/10.19616/j.cnki.bnjj.2023.05.008> (2023).
33. Li, Z. K. & Wu, X. Y. A research on the financial constraints and corporate investment based on an analysis of the negative moderation of family control. *Sci. Res. Manag.* **38**(2), 101–111. (2017). <https://doi.org/10.19571/j.cnki.1000-2995.2017.02.013>
34. Xu, J. Q., Shi, K., Xu, L. P. & Xin, Y. Managerial power delegation and efficiency loss of executive compensation incentives. *Contemp. Finance Econ.* **1**, 86–99. <https://doi.org/10.13676/j.cnki.cn36-1030/f.20230927.001> (2024).
35. Li, S. & Zhang, X. Can digital transformation of enterprise improve the information environment of the capital market? — Evidence from the analyst's perspective. **97** 103773. <https://doi.org/10.1016/j.iref.2024.103773> (2025). *Int. Rev. Econ. Finance.*
36. Driskill, M., Kirk, M. P. & Tucker, J. W. Concurrent earnings announcements and analysts' information production. *Account. Rev.* **95**(1), 165–189. (2020). <https://doi.org/10.2308/accr-52489>
37. Wu, F., Hu, H. Z., Lin, H. Y. & Ren, X. Y. Enterprise digital transformation and capital market performance: empirical evidence from stock liquidity. *Manag. World.* **(7)**, 130–144. <https://doi.org/10.19744/j.cnki.11-1235/f.2021.0097> (2021). 37.
38. Warren, J. D., Moffitt, K. C. & Byrnes, P. How big data will change accounting. *Account. Horiz.* **29**, 397–407. (2015). <https://doi.org/10.2308/achc-51069>
39. Chen, Q. & Jiang, W. Analysts' weighting of private and public information. *Rev. Financ. Stud.* **19** (1), 319–355. <https://doi.org/10.1093/rfs/hhj007> (2006).
40. Gu, Z., Gu, C. & Zhang, C. Analyst forecast behavior under trade uncertainty: evidence from China. *Financ. Res. Lett.* **85(E)**, 108245. <https://doi.org/10.1016/j.frl.2025.108245> (2025).
41. Xie, X. M. & Zhu, Q. W. How can green innovation solve the dilemmas of harmonious coexistence? *Manag. World.* **37** (1), 128–149. <https://doi.org/10.19744/j.cnki.11-1235/f.2021.0009> (2021).
42. Li, P., Li, X. & Wu, Q. Digitalization drives sustainability: how digital trade enhances corporate ESG performance through innovation, internationalization and transparency. **101** 104248. <https://doi.org/10.1016/j.iref.2025.104248> (2025).
43. Lin, H., Chen, H., Tang, H. & Chen, M. Can the Chinese cultural consumption pilot policy facilitate sustainable development in the agritourism economy? *Agric.* **15**(11), 1117. (2025). <https://doi.org/10.3390/agriculture1511117>

## Author contributions

Yao Jingjing: Responsible for the topic selection of the thesis and the overall review of the thesis content. Zhang Yun: Responsible for drafting the initial manuscript of the thesis and revising the manuscript in response to review comments and content optimization needs. Sun Yinan: Responsible for sorting, verifying, and organizing the research data required for the thesis. Bo Qian: Responsible for collecting, sorting, and collating the literature materials (including references and supporting documents) for the thesis.

## Funding

This work is supported by the National Social Science Fund Youth Project of China (Grant 21CJY040), the Key Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (Grant 2021SJJZDA139), and the Jiangsu University Scientific Research Project Establishment (Grant 24C119).

## Declarations

### Competing interests

The authors declare no competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Additional information

Correspondence and requests for materials should be addressed to Y.Z.

Reprints and permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025