International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 8229-8240

https://doi.org/10.70517/ijhsa464704

Improving the K-means algorithm to measure the impact of ESG ratings on spatial heterogeneity in total factor productivity: A research study

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Abstract This paper reviews and defines ESG performance and total factor productivity (TFP) of firms, and proposes a research design. Using a sample of Chinese A-share listed companies from 2015 to 2024, the study empirically tests the impact of ESG ratings on firm TFP and its underlying mechanisms. The findings are as follows: (1) In a replacement test of the dependent variable, the regression coefficient of ESG disclosure on TFP from the previous period is 0.003, and it is significantly positive at the 1% level. By replacing the explanatory variable, the TFP calculated using the LP method based on Huazheng ESG is significantly positive at the 1% level, validating the robustness of the conclusion. (2) ESG indirectly enhances TFP through two pathways: incentivizing technological innovation and alleviating financing constraints. (3) Digital transformation positively moderates the relationship between ESG and TFP. Further analysis indicates that environmental performance has a U-shaped relationship with TFP, while social and governance performance have a linear positive impact.

Index Terms ESG, total factor productivity, technological innovation, financing constraints, digital transformation

I. Introduction

The concept of ESG can be traced back to 2004, when the term was first introduced in the United Nations' “Report on the Environmental Project Finance Initiative” [1]. ESG stands for environmental, social, and corporate governance. It differs from metrics that focus solely on a specific aspect of a company's performance, instead comprehensively evaluating a company's sustainable development and the social value it generates across the three dimensions of environment, society, and corporate governance [2], [3]. Since its emergence, the ESG concept has seen rapid global growth. According to the Global Sustainable Investment Alliance (GSIA), the global ESG asset size is projected to exceed 53 trillion U.S. dollars by 2025 [4].

The ESG philosophy aligns closely with China's “five-in-one” overall layout and the new development philosophy of “innovation, coordination, green development, openness, and shared benefits,” as well as with the strategic framework of the “dual carbon” goals. Although China has been relatively late in promoting ESG development, the Chinese government has accelerated the construction of the ESG system in recent years to enhance companies' ability for healthy growth and advance toward the goal of high-quality socio-economic development [5]-[7]. According to relevant statistical data, the proportion of Chinese listed companies disclosing ESG information has significantly increased year-on-year. Over 30% of A-share listed companies have separately compiled and published 2022 ESG-related reports, demonstrating the growing importance Chinese enterprises place on ESG principles [8].

Numerous experts and scholars have conducted research on ESG information disclosure. On one hand, many scholars emphasize the necessity and importance of ESG information disclosure. Fairchild, R., et al. [9] noted in their research that various countries and regions worldwide have introduced a series of policies and regulations requiring companies to actively disclose ESG information. Building on this, scholars have further emphasized the importance of focusing on the quality of ESG disclosure. Yu, E, and others [10] found that some companies engage in “greenwashing,” where they disclose a large amount of unaudited ESG information to establish a positive image, but in reality, this ESG information lacks authenticity and reliability, which to some extent hinders the promotion of ESG principles. Wong, W et al. [11] conducted an in-depth exploration of the impact of ESG on Malaysian companies, analyzing that ESG significantly improved the Tobin's Q value of companies.

On the other hand, the research conclusions of scholars on the impact of ESG performance on corporate value have not yet been unified, and a small number of scholars believe that ESG performance has nothing to do with corporate value, or that ESG performance negatively affects corporate value. Atan, R et al. [12] found that neither the ESG composite score nor the sub-score had a significant impact on corporate value through regression analysis

of panel data. Barnea, A. and Rubin, A [13] pointed out that management may increase ESG investment for the purpose of improving its own reputation, and that when the total amount of resources is constant, excessive ESG investment will occupy the limited resources of the enterprise, squeeze other investments, increase the financial risk of the enterprise, and damage the interests of shareholders and the value of the bank. Based on this, some scholars believe that the ESG performance of companies will have a negative impact on enterprises. Garcia, A et al. [14] selected 365 companies from BRICS countries and concluded that there is an inverted U-shaped relationship between ESG performance and corporate systemic risk.

A firm's total factor productivity (TFP) is not only subject to fluctuations caused by changes in external environmental factors but is also closely related to the firm's own behavior [15]. Existing literature on the factors influencing firm TFP can be categorized into two types: macro-external factors and micro-internal factors. Regarding macro-external factors, scholars have primarily conducted research from the perspectives of market characteristics, policy implementation, government fiscal behavior, and the level of internet development [16], [17]. From the perspective of market characteristics, Larrain, M, and Stumpner, S, et al. [18] conducted an empirical analysis of 10 companies located in Eastern European countries. The results indicated that the opening of capital markets can help enterprises overcome funding shortages, optimize production technology and equipment, thereby improving capital allocation and promoting TEP growth. Li, Z, and Lv, B [19] measured TEP for Chinese industrial enterprises, finding that the average growth rate of TEP for Chinese industrial enterprises was 2.58% between 2007 and 2017, with significant differences in TEP across different enterprise characteristics. Xu, X et al. [20] employed growth accounting methods and total TFP indicators to study TFP across various industry levels in China. The study found that capital investment and TFP were the key drivers of economic growth during the period from 1985 to 2015. Feder, C [21] proposed a new TEP measurement method that accounts for technological change factors, distinguishing between neutral and biased effects, and remains valid under different measurement units and changes in factor costs. Wiech, B et al. [22] proposed a framework for understanding profitability and productivity changes at the enterprise level and conducted a critical analysis of the TEP definition. Wang, X et al. [23] developed a TEP measurement index for China's construction industry and analyzed its spatial differences, finding that TEP has achieved steady improvement due to technological efficiency and scale progress, and exhibits a unique staircase-like distribution across regions.

Research on the impact of ESG ratings on firm-level total factor productivity is currently limited, but the conclusions reached are consistent, indicating that firm ESG ratings positively influence total factor productivity. Ma, J et al. [24] found that there was a positive correlation between ESG ratings and TFP for Chinese listed companies during the 2010–2020 period. The specific mechanism is that ESG improves TFP by reducing financial constraints and enhancing innovation investments, with this effect being more pronounced in state-owned enterprises and high-pollution industries. Yu, X, and Chen, Y [25] found that ESG advantages significantly enhance TFP, particularly for large state-owned enterprises, labor-intensive enterprises, and less mature companies. This effect is achieved by reducing labor costs and agency costs, thereby supporting high-quality development. Ding, H et al. [26] found that ESG ratings have a positive impact on corporate TFP, with financial constraints and R&D investment playing an intermediary role. This study provides reference insights for corporate strategic planning and sustainable development. Zhang, Y et al. [27] found that superior ESG ratings can enhance TFP in Chinese textile firms through mechanisms such as green innovation and human capital, providing guidance for firms to improve their ESG levels and achieve sustainable development. Yang, F et al. [28] found that ESG performance enhances TFP in downstream customers by alleviating financing constraints, while monopoly power exerts a negative moderating effect on this relationship. Gu, Y et al. [29] examined the interrelationships among ESG performance, total factor productivity (TFP), and energy efficiency (EE) in Chinese listed companies from 2010 to 2022. They found that ESG contributes to improving TFP and EE, and this impact varies depending on ownership structure and environmental regulations, revealing optimal pathways and potential risks for sustainable development.

This paper first outlines the research design, including variable selection and model construction. The Huazheng ESG ratings of each listed company are used as the explanatory variable, while total factor productivity (TFP), which reflects a company's long-term growth potential, serves as the dependent variable. Robustness tests were conducted by swapping the explanatory and dependent variables. Using a mediation effect model, the study discusses the role of technological innovation and financing constraints as mediating variables in the process by which corporate ESG performance affects corporate performance. Based on a moderation effect model, the study examines the impact of corporate digital transformation on total factor productivity. The ESG indicators used as explanatory variables are broken down into three dimensions, and their respective impacts on productivity are studied.

II. Research design on the impact of ESG ratings on total factor productivity of enterprises

With the deepening of the concept of sustainable development, environmental, social, and corporate governance (ESG) performance has become an important indicator for measuring the long-term value of enterprises. Existing research has mostly focused on the impact of ESG on corporate financial performance, while there has been insufficient discussion on how it affects total factor productivity (TFP) through non-financial channels. This paper aims to fill this research gap by systematically analyzing the mechanism and boundary conditions of ESG ratings on corporate TFP.

II. A. Variable Selection

II. A. 1) Dependent variable

In studies examining the impact of ESG performance on corporate performance, financial metrics and market value are primarily selected as performance indicators, such as return on assets (ROA) and Tobin's Q. Since these financial metrics and market value indicators are based on financial statements, they can only reflect a company's past performance and cannot reflect more future information or the company's sustainability. Therefore, it is proposed that total factor productivity (TFP) be selected when studying the impact of ESG performance on corporate performance. TFP serves as an indicator of a company's overall resource allocation efficiency, combining forward-looking characteristics with consistency with future corporate value maximization.

The dependent variable in this study is TFP calculated using the LP method, which uses intermediate input indicators as proxy variables for investment amounts, effectively avoiding measurement errors and thereby more accurately measuring a company's TFP. The output variable Y_{it} represents operating revenue, labor input L_{it} represents the total number of employees, capital input K_{it} represents net fixed assets, and M_{it} denotes intermediate input = sales expenses + management expenses + financial expenses - cash paid to employees and for employees - depreciation and amortization. The estimation equation for TFP is as follows:

$$\ln\left(Y_{it}\right)=\beta_0+\beta_t+\ln\left(L_{it}\right)+\beta_k\ln\left(K_{it}\right)+\beta_m\ln\left(M_{it}\right)+\varepsilon_{it} \tag{1}$$

II. A. 2) Explanatory variables

The explanatory variable in this paper is corporate ESG performance, which directly uses ESG scores from third-party rating agencies.

ESG evaluation systems were established earlier in foreign countries, so the ESG rating systems constructed by third-party institutions abroad are already relatively mature. These include ESG ratings from professional data companies such as FTSE Russell, MSCI, and Dow Jones, as well as ESG ratings from international organizations with NGO backgrounds. China, however, began developing ESG ratings relatively late, so there are fewer third-party institutions with well-established ESG rating systems. These include the ESG ratings developed by the Green Finance Research Institute of Central University of Finance and Economics, the China Chengxin Green Finance ESG ratings, the Shangdao Ronglv ESG ratings, and the Huazheng ESG ratings.

The Huazheng ESG rating primarily targets A-share listed companies and incorporates indicators tailored to China's market, policies, and listed company characteristics, covering a wide range of indicators and years. The data used primarily consists of publicly disclosed information from listed companies, supplemented by corporate CSR reports, news reports, regulatory announcements, and other sources. It also includes unique data obtained through machine learning methods such as web crawling and semantic analysis. Additionally, specific indicators are assigned corresponding weights based on the industry to which the listed company belongs, enabling precise ESG evaluation. Therefore, this paper selects the Huazheng ESG rating of the company as the core explanatory variable. Huazheng categorizes the ESG ratings of A-share listed companies into nine tiers from AAA to C. This paper assigns values from 9 to 1 to companies based on their ESG rating performance, from highest to lowest.

II. A. 3) Control variables

A total of eight control variables were selected for this study, namely enterprise size, debt-to-equity ratio, ownership structure, enterprise age, return on assets, cash flow ratio, equity concentration, and fixed asset ratio.

II. A. 4) Mediating variables

(1) Technological Innovation (TI)

Patent applications and patent grants have a lag effect and may not timely reflect the impact of technological innovation on the improvement of a company's total factor productivity. Research and development (R&D) investment is the core behavior of technological innovation. Therefore, this paper uses the ratio of a company's R&D investment to its total assets to measure its technological innovation.

(2) Financing Constraints (KZ)

To measure financing constraints (KZ) on enterprises, the following steps are taken to construct the KZ index, which measures the degree of financing constraints on enterprises.

1) Let $KZ1 = CF_{it} / ASSET_{it-1}$, $KZ2 = DIV_{it} / ASSET_{it-1}$, $KZ3 = CASH_{it} / ASSET_{it-1}$, $KZ4 = LEV_{it}$, and $KZ5 = Q_{it}$, where $ASSET_{it-1}$ is the total assets from the previous period, CF_{it} is the operating cash flow, DIV_{it} is the cash dividend, $CASH_{it}$ is the cash holdings, and LEV_{it} is the debt-to-equity ratio, Q_{it} is Tobin's Q value. If $KZi\left(i = 1,2,3,4,5\right)$ is greater than the median, then KZi is set to 1; otherwise, it is set to 0.

2) Construct the KZ index equation: $KZ = KZ1 + KZ2 + KZ3 + KZ4 + KZ5$.

3) Construct the model (2) using ordered logistic regression, with the above KZ index as the dependent variable, to estimate the regression coefficients of each variable.

4) Using the above estimation results, calculate the degree of financing constraints faced by the company. A higher KZ index indicates a higher degree of financing constraints faced by the company.

$$KZ_{it} = \alpha_1 \frac{CF_{it}}{ASSET_{it-1}} + \alpha_2 \frac{DIV_{it}}{ASSET_{it-1}} + \alpha_3 \frac{CASH_{it}}{ASSET_{it-1}} + \alpha_4 LEV_{it} + \alpha_5 Q_{it} \tag{2}$$

II. A. 5) Adjustment variables

Based on the availability of data and the difficulty of measurement, this paper measures enterprise digital transformation by taking the logarithm of the frequency of keywords related to "enterprise digital transformation" in annual reports, plus one. Specifically: First, a corporate digital transformation terminology dictionary is constructed, summarizing and organizing keywords related to corporate digital transformation, and building a dictionary covering aspects such as artificial intelligence technology, cloud computing technology, blockchain technology, big data technology, and digital applications; second, Python web scraping functionality is used to collect and organize the frequency of keywords related to corporate digital transformation from the annual reports of listed companies; third, the corporate digital transformation degree indicator is constructed, with the corporate digital transformation index calculated as ln(frequency of keywords related to "corporate digital transformation" + 1).

II. B.Model Settings

Based on the above assumptions, this paper constructs a theoretical model with total factor productivity (TFP) as the dependent variable, corporate ESG practices as the explanatory variable, corporate size and debt-to-equity ratio as control variables, technological innovation, financing constraints, and inefficient investment as mediating variables, and corporate digital transformation and executive team stability as moderating variables, as shown in Figure 1.

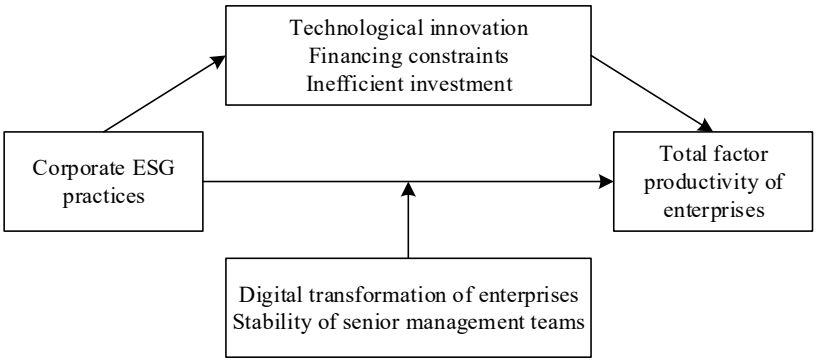

Figure 1: Theoretical model

II. B. 1) Benchmark regression model

In order to examine the impact of corporate ESG practices on total factor productivity, the following regression model was first established:

$$\begin{aligned} TFP_{it} &= \beta_0 + \beta_1 ESG_{it} + \beta_2 Size_{it} + \beta_3 Age_{it} \\ &+ \beta_4 Soe_{it} + \beta_5 Lev_{it} + \beta_6 Roa_{it} \\ &+ \beta_7 Cashflow_{it} + \beta_8 Top1_{it} \\ &+ \beta_9 Fixs_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{3}$$

In this equation, TFP_{it} denotes the total factor productivity of firm i in year t, β_0 is the constant term, $\beta_i\,(i=1,2,3\ldots)$ are the coefficients of each variable, where i and t represent the firm and year, respectively, μ_i is the individual fixed effect, γ_t is the time fixed effect, and ε_{it} is the random disturbance term.

II. B. 2) Intermediary Model

To explore the transmission path of corporate ESG practices on total factor productivity, we conducted a mediation effect test. The mediation effect analysis first used stepwise regression to test the mediation effect. If the stepwise regression method was not significant, the Bootstrap method was used for testing.

The stepwise regression test model is as follows:

$$TFP_{it} = \beta_0 + \beta_1 ESG_{it} + \beta_j \sum control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{4}$$

$$Median_{it} = \alpha_0 + \alpha_1 ESG_{it} + \alpha_j \sum control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{5}$$

$$TFP_{it} = \theta_0 + \theta_1 ESG_{it} + \theta_2 Median_{it} + \theta_j \sum control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{6}$$

In models (5) and (6), $Median_{it}$ represents the mediating variables, namely technological innovation and financing constraints. If the test results show that α_1 and θ_1, θ_2 are significant, this indicates that the mediating effect is significant. Based on the previous analysis, corporate ESG practices may influence a company's total factor productivity through technological innovation and financing constraints. If α_1 and θ_2 are not significant, the Bootstrap method is used for mediation testing.

II. B. 3) Adjustment model

Construct a model (7) to verify the moderating effect of corporate ESG practices on the impact of digital transformation on total factor productivity.

$$\begin{aligned} TFP_{it} &= \rho_0 + \rho_1 ESG_{it} + \rho_2 Moderate_{it} \\ &+ \rho_3 ESG_{it} \times Moderate_{it} \\ &+ \rho_j \sum control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{7}$$

Among them, $Moderate_{it}$ is the moderating variable, i.e., corporate digital transformation. If ρ_3 is significantly positive in the model, it indicates that the moderating variable positively reinforces the promotion of ESG practices on total factor productivity. If the interaction term coefficient ρ_3 is significantly negative, it indicates that the moderating variable has an inhibitory effect on the promotion of ESG practices on total factor productivity.

III. Empirical Analysis of the Impact of ESG Ratings on Total Factor Productivity of Enterprises

This paper uses publicly disclosed data from Chinese A-share listed companies from 2015 to 2024 as its sample. Samples that were specially marked as ST during the sample period and financial and insurance companies were excluded, as were samples with severe data deficiencies. To prevent extreme values from affecting the robustness of the results, extreme value processing was performed at the 1% and 99% percentiles. The final dataset comprises 7,465 observations from 1,863 listed companies over a 10-year period. Company shareholder structure and financial data are sourced from the Guotai An database, media reports on listed companies are sourced from the China Research Data Service Platform (CNRDS), and the dependent and instrumental variables are calculated using Stata software.

III. A. Descriptive statistics

The descriptive statistics of the variables involved in this paper are shown in Table 1. The mean value of total factor productivity (TFP) for enterprises is 15.382, with a standard deviation of 1.038, indicating significant differences in production efficiency among different enterprises. The mean value of ESG ratings is 4.048, showing a distinct

dispersion pattern. The technological innovation indicators show that the average R&D intensity of the sample enterprises is 1.8%. The financing constraint index indicates that the financing environment of the sample enterprises exhibits significant heterogeneity. The digital transformation index of the enterprises exhibits a right-skewed distribution. Regarding control variables, the average years in operation of the sample enterprises is 20.587 years, state-owned enterprises account for 29.7%, and the largest shareholder holds a 35.381% stake, reflecting a relatively concentrated equity structure.

Table 1: Descriptive Statistics

Variable	Observed value	Average value	Standard deviation	Minimum value	Maximum value
TFP	7465	15.382	1.038	12.647	20.763
ESG	7465	4.048	1.376	1	8
Size	7465	23.684	1.184	20.048	27.115
Lev	7465	0.506	0.152	0.033	0.894
Soe	7465	0.297	0.336	0	1
Age	7465	20.587	4.183	5	41
Roa	7465	0.051	0.038	-0.286	0.255
Cashflow	7465	0.054	0.071	-0.204	0.302
Top1	7465	35.381	11.186	6.386	78.222
Fixs	7465	0.205	0.128	0.003	0.616
TI	7465	0.018	0.025	0	0.152
KZ	7465	2.847	1.635	-1.092	7.533
Digital	7465	1.726	1.284	0	5.214

In summary, through the analysis of descriptive statistical results, this paper provides an overview of the basic characteristics of the sample companies in terms of total factor productivity, ESG performance, and other financial and structural features, providing preliminary background information for subsequent analysis. These data reflect the differences among the sample companies across various dimensions, providing a rich data foundation for in-depth research into the relationship between ESG performance and total factor productivity.

III. B. Analysis of regression results

III. B. 1) Replacing the explanatory variable

This paper estimates firm-level total factor productivity (TFP) using the SFA method based on a transcendental log production function with three input variables. A regression analysis is conducted with TFP_SFA (total factor productivity estimated using the SFA method) as the dependent variable. The results of replacing the dependent variable are shown in Table 2. The results indicate that the regression coefficient for ESG information disclosure on TFP from the previous period is 0.003, and it is significantly positive at the 1% level. Further decomposition of the three dimensions of ESG ratings reveals that the regression coefficients for environmental and corporate governance information disclosure are 0.002 (significant at the 1% level) and 0.003 (significant at the 1% level), respectively, while the coefficient for social responsibility information disclosure, though positive (0.001), is only significant at the 10% level. In terms of model fit, the R^2 values for all four regression groups exceed 0.75, indicating that the model has good explanatory power.

Table 2: Test results for replacing the explained variables

	(1) F.TFPsfa	(2) F.TFPsfa	(3) F.TFPsfa	(4) F.TFPsfa
ESG	0.003*** (5.038)			
E		0.002*** (4.019)		
S			0.001* (1.486)	
G				0.003*** (3.187)
Size	-0.017** (-2.381)	-0.018** (-2.556)	-0.021** (-1.958)	-0.016* (-2.019)
Lev	-0.033 (-1.497)	-0.035 (-1.377)	-0.034 (-1.399)	-0.031 (-1.422)
Soe	-0.042* (-1.824)	-0.043* (-1.798)	-0.041* (-1.763)	-0.042* (-1.806)
Age	0.031** (2.085)	0.029** (2.034)	0.030* (1.995)	0.028** (2.056)
Roa	0.327*** (6.882)	0.325*** (6.765)	0.329*** (6.808)	0.326*** (6.794)
Cashflow	0.198*** (7.038)	0.189*** (6.937)	0.194*** (6.994)	0.192*** (6.973)

Top1	0.009 (0.504)	0.008 (0.497)	0.009 (0.501)	0.009 (0.499)
Fixs	-0.058** (-3.327)	-0.059** (-3.341)	-0.057** (-3.296)	-0.056** (-3.313)
Individual fixed effect	Yes	Yes	Yes	Yes
Time-fixed effect	Yes	Yes	Yes	Yes
Constant term	1.127*** (9.038)	1.133*** (8.947)	1.131*** (8.836)	1.102*** (8.773)
Observed value	7465	7328	7391	7388
R^2	0.761	0.758	0.761	0.761

III. B. 2) Replacement of explanatory variables

This paper calculates the average values for each of the four quarters of the year (ESGhz). The test results after replacing the explanatory variables are shown in Table 3. The regression results after replacing the explanatory variables show that the Huazheng ESG has a significant positive effect on the total factor productivity of enterprises calculated using the LP method at the 1% level, and the empirical analysis conclusions are robust.

Table 3 Test results after replacing the explanatory variables

	(1) F.TFPlp	(2) F.TFPlp
ESGhz	0.046*** (6.737)	0.025*** (3.536)
Size		0.503*** (40.376)
Lev		0.242*** (5.588)
Soe		-0.058* (1.756)
Age		0.033 (1.588)
Roa		0.387*** (5.038)
Cashflow		0.285*** (4.432)
Top1		-0.074* (1.257)
Fixs		-0.501*** (-7.486)
Individual fixed effect	Yes	Yes
Time-fixed effect	Yes	Yes
Constant term	8.664*** (422.686)	-1.646*** (-7.037)
Observed value	22686	22671
R^2	0.906	0.948

III. C. Testing for mediating effects

III. C. 1) Technological Innovation

The results of the mediation effect test for technological innovation levels are shown in Table 4. First, Column (2) of the table shows the impact of ESG performance on technological innovation levels. It can be seen that the regression coefficient between ESG ratings and technological innovation levels is 0.001, with a positive coefficient that is statistically significant at the 1% confidence level. This indicates that an improvement in a company's ESG rating can significantly increase its technological innovation levels, meaning that a company's ESG performance has a positive impact on its innovation levels. Second, column (3) in the table examines the impact of ESG and technological innovation levels on a company's total factor productivity. The regression results show that after incorporating technological innovation level as a mediating variable, the coefficients for ESG ratings and technological innovation levels are both positive and significant at the 1% confidence level. This indicates that technological innovation levels play a mediating role in the process by which ESG performance promotes a company's total factor productivity, meaning that improvements in a company's ESG performance can increase its technological innovation levels, which in turn enhances the firm's TFP.

Table 4: Test Results of the mediating effect of technological innovation level

	(1) TFP	(2) TI	(3) TFP
ESG	0.004*** (6.127)	0.001*** (3.852)	0.003*** (5.642)
TI			0.198*** (7.463)
Size	-0.019** (-2.537)	-0.003 (-1.284)	-0.018** (-2.481)
Lev	-0.035 (-1.502)	-0.012 (-0.873)	-0.033 (-1.487)
Soe	-0.045* (-1.896)	-0.008 (-0.742)	-0.043* (-1.872)
Age	0.030** (2.104)	0.006 (1.024)	0.029** (2.083)

Roa	0.135*** (4.012)	0.022** (2.317)	0.131*** (3.972)
Cashflow	0.203*** (7.215)	0.031** (2.485)	0.197*** (7.128)
Top1	0.011 (0.527)	0.002 (0.318)	0.009 (0.521)
Fixs	-0.059** (-2.341)	-0.011 (-1.127)	-0.057** (-2.315)
Constant term	1.143*** (9.217)	0.024** (2.403)	1.138*** (9.184)
Observed value	7465	7465	7465
R^2	0.763	0.185	0.768

III. C. 2) Financing constraints

The results of the mediation effect test for financing constraints are shown in Table 5. First, Column (2) tests the impact of ESG on financing constraints. The regression results indicate that, after controlling for other variables, ESG is significantly negatively correlated with financing constraints at the 1% level, with a coefficient of -0.317, meaning that good ESG performance can effectively reduce a company's financing constraints. Second, with total factor productivity as the dependent variable, ESG performance and financing constraint indicators are simultaneously included in the regression model to test the impact of financing constraints and ESG performance on firm total factor productivity. As shown in Column (3), the coefficient for the negative impact of financing constraints on firm total factor productivity is -0.127, and it is significant at the 1% confidence level. Meanwhile, the positive relationship between ESG performance and TFP remains unchanged. Therefore, a company's ESG performance can enhance TFP by alleviating financing constraints. That is, financing constraints play a mediating role in the process where ESG performance influences TFP. Companies can significantly alleviate financing constraints by improving their ESG governance and enhancing their ESG levels, thereby increasing their TFP.

Table 5: Test Results of the mediating effect of financing constraints

	(1) TFP	(2) KZ	(3) TFP
ESG	0.004*** (6.127)	-0.317*** (-4.892)	0.003*** (5.843)
KZ			-0.127*** (4.127)
Size	-0.019** (-2.537)	0.284*** (4.215)	-0.017** (-2.481)
Lev	-0.035 (-1.502)	1.873*** (8.342)	-0.021 (-1.127)
Soe	-0.045* (-1.896)	-0.128 (-1.284)	-0.046* (-1.902)
Age	0.030** (2.104)	-0.042 (-1.127)	0.030** (2.098)
Roa	0.135*** (4.012)	-1.873*** (-6.842)	0.120*** (3.872)
Cashflow	0.203*** (7.215)	-0.842*** (-5.327)	0.196*** (7.128)
Top1	0.011 (0.527)	-0.031 (-0.842)	0.010 (0.525)
Fixs	-0.059** (-2.341)	0.127 (1.284)	-0.058** (-2.328)
Constant term	1.143*** (9.217)	3.127*** (7.842)	1.168*** (9.432)
Observed value	7465	7465	7465
R^2	0.763	0.342	0.766

III. D. Moderation effect test

The moderating effect of corporate digital transformation on ESG and total factor productivity is shown in Table 6. Using a stepwise regression method, the first step involves including only control variables in the model, the second step involves adding the independent variable ESG and the moderator variable, and the third step involves including the centered product term of the independent variable ESG and the moderator variable in the model. As shown in column (2) of the table, the regression coefficient between corporate digital transformation and total factor productivity is 0.021, and it is positive at the 1% confidence level, indicating that corporate digital transformation has a positive impact on corporate total factor productivity. In column (3), the regression coefficient for the product term between ESG performance and TFP is 0.019, and it is significant at the 1% level, indicating that digital transformation plays a positive moderating role in the process where ESG performance influences TFP. That is, the higher the level of digital transformation, the stronger the positive effect of ESG performance on TFP.

Table 6: The Moderating Effect of Enterprise Digital Transformation

	(1) TFP	(2) TFP	(3) TFP
ESG		0.003*** (4.915)	0.002** (2.537)
Digital		0.021*** (3.842)	0.019*** (3.672)

ESG*Digital			0.005*** (3.185)
Size	-0.018** (-2.481)	-0.017** (-2.427)	-0.016** (-2.318)
Lev	-0.032 (-1.427)	-0.031 (-1.402)	-0.029 (-1.385)
Soe	-0.043* (-1.872)	-0.042* (-1.853)	-0.041* (-1.827)
Age	0.029** (2.083)	0.028** (2.064)	0.027** (2.042)
Roa	0.131*** (3.972)	0.129*** (3.927)	0.128*** (3.892)
Cashflow	0.197*** (7.128)	0.195*** (7.083)	0.194*** (7.042)
Top1	0.009 (0.521)	0.009 (0.518)	0.008 (0.512)
Fixs	-0.057** (-2.315)	-0.056** (-2.302)	-0.055** (-2.287)
Individual fixed effect	Yes	Yes	Yes
Time-fixed effect	Yes	Yes	Yes
Constant term	1.138*** (9.184)	1.127*** (9.127)	1.124*** (9.083)
Observed value	7465	7465	7465
R^2	0.768	0.771	0.774

III. E. Segmentation Dimension Analysis

To examine the impact of the three ESG dimensions on a company's total factor productivity, this paper constructs the following model for OLS regression. This model is essentially the same as the main regression model, except that the explanatory variable ESG indicators are broken down into three dimensions, E, S and G, to study their respective effects on productivity.

$$\begin{aligned} TFP\_LP_{i,t} = {} & \alpha_0 + \alpha_1 E_{i,t-1} / S_{i,t-1} / G_{i,t-1} + \alpha_2 Age_{i,t} \\ & + \alpha_3 Size_{i,t} + \alpha_4 Roa_{i,t} + \alpha_5 Kperl_{i,t} + \alpha_6 Subsidy_{i,t} \\ & + \alpha_7 Growth_{i,t} + \alpha_8 Lev_{i,t} + \alpha_9 HHI_{i,t} \\ & + \alpha_{10} Soe_{i,t} + \sum Year + \sum Industry + \varepsilon_{i,t} \end{aligned} \tag{8}$$

Among these, $TFP\_LP_{i,t}$ denotes the total factor productivity of the company in period t calculated using the LP method, $E_{i,t-1}$, $S_{i,t-1}$, and $G_{i,t-1}$ represent the company's environmental performance, social performance, and corporate governance performance in period $t-1$ respectively, using the CSI ESG rating indicators; while controlling for other variables at the company level.

III. E. 1) Environment

During the transition period from high-speed economic growth to high-quality development, how to safeguard the Earth's environment upon which we depend for survival, how to promote healthy and sustainable economic development, and how to effectively balance the relationship between the two have become hot topics in Chinese academic research. Under the significant pressure of environmental regulations, a company's environmental protection efforts can lead to a substantial increase in costs beyond its core production and operations, such as pollution control and emissions management costs. These costs erode the resources a company has available for production and operations, effectively imposing additional constraints on its production function. This limits the company's operational flexibility, increases the challenges in its supply chain and sales processes, reduces its market competitiveness, and ultimately results in a decline in its total factor productivity. However, the negative effects of environmental protection measures prompt companies to focus on internal resource allocation efficiency and mitigate the constraints imposed by environmental regulations through technological innovation investments. As the returns on R&D investments gradually materialize, the positive effects of “innovation compensation” will eventually outweigh the negative effects of “compliance costs,” ultimately promoting productivity growth.

The regression results of the nonlinear model linking environmental performance and TFP are shown in Table 7. There is a U-shaped relationship between a firm's previous environmental protection performance and its total factor productivity. This is because environmental governance is challenging and time-consuming, and environmental protection is an investment with high upfront costs and slow returns. That is, the effects of environmental protection are not immediate and require a significant amount of time to materialize. This means that initial environmental protection investments act as a cost for firms, diverting funds from production operations and reducing resource allocation efficiency, thereby causing TFP to decline; However, as the returns from environmental protection investments are realized—primarily manifested in the outcomes and application of R&D investments—the “innovation compensation” effect drives TFP growth, fundamentally enhancing the firm's input-output efficiency.

Table 7: Regression Results of Environmental Protection Performance

	(1) TFP	(2) TFP
E_{t-1}	-2.974*** (-8.936)	-0.897*** (-5.037)
E_{t-1}^2	3.186*** (9.947)	0.994*** (4.972)
Size		0.112*** (3.825)
Lev		-0.187*** (-3.628)
Soe		-0.068** (-2.476)
Age		0.015*** (2.846)
Roa		1.735*** (6.187)
Cashflow		0.397*** (4.856)
Top1		0.002* (1.822)
Fixs		-0.295*** (-4.501)
Individual fixed effect	Yes	Yes
Time-fixed effect	Yes	Yes
Constant term	9.375*** (32.687)	6.835*** (17.113)
Observed value	7465	7465
R^2	0.388	0.725

III. E. 2) Society

The improvement in a company's total factor productivity is the result of coordinated development throughout the entire production and operation process, and is closely related to stakeholders such as the government, suppliers, customers, and employees. A company's fulfillment of its social responsibilities is a manifestation of its accountability to these stakeholders. From the perspective of new institutional economics, corporate social responsibility exerts a non-institutional constraint on a company's profit-seeking behavior.

The regression results for the relationship between corporate social responsibility performance and total factor productivity are shown in Table 8. Without considering control variables, there is a significant positive correlation between a company's previous period social responsibility performance and total factor productivity. Even after controlling for variables in the regression, the two remain positively correlated at the 1% significance level. These regression results indicate that actively fulfilling social responsibility can significantly enhance a company's productivity.

Table 8: Regression Results of Corporate Social Responsibility Performance

	(1) TFP	(2) TFP
S_{t-1}	0.702*** (9.058)	0.311*** (5.283)
Size		0.118*** (4.027)
Lev		-0.197*** (-3.842)
Soe		-0.073** (-2.318)
Age		0.014*** (2.728)
Roa		1.782*** (6.327)
Cashflow		0.418*** (5.127)
Top1		0.003* (1.927)
Fixs		-0.302*** (-4.627)
Individual fixed effect	Yes	Yes
Time-fixed effect	Yes	Yes
Constant term	8.586*** (30.386)	7.027*** (16.377)
Observed value	7465	7465
R^2	0.337	0.718

III. E. 3) Corporate Governance

With the development of the economy, the agency problems arising from the separation of ownership and management rights in enterprises have attracted widespread attention from both the academic and practical communities. An effective corporate governance mechanism can promote scientific decision-making by management through supervision and incentives, suppress inefficient investment behavior, effectively improve

agency efficiency, reduce agency costs, and drive the continuous optimization of enterprise resource allocation and the continuous improvement of production efficiency.

The regression results for corporate governance performance and total factor productivity are shown in Table 9. Without considering control variables, there is a significant positive correlation between a firm's previous period corporate governance performance and total factor productivity. Even after controlling for variables in the regression, the two remain positively correlated at the 1% significance level. These regression results indicate that strengthening governance efforts, enhancing governance effectiveness, and reducing governance costs have a significant promotional effect on the growth of total factor productivity.

Table 9: Regression Results of Corporate Governance Performance of enterprises

	(1) TFP	(2) TFP
S_{t-1}	0.785*** (11.654)	0.285*** (5.056)
Size		0.124*** (4.175)
Lev		-0.203*** (-4.011)
Soe		-0.078** (-2.247)
Age		0.016*** (3.054)
Roa		1.832*** (6.475)
Cashflow		0.439*** (5.376)
Top1		0.004* (2.018)
Fixs		-0.315*** (-4.927)
Individual fixed effect	Yes	Yes
Time-fixed effect	Yes	Yes
Constant term	9.018*** (38.467)	6.873*** (18.114)
Observed value	7465	7465
R^2	0.473	0.745

IV. Conclusion

This paper uses Chinese A-share listed companies from 2015 to 2024 as the research sample to conduct an in-depth analysis of the impact mechanism and role of corporate ESG performance on their performance.

(1) In a replacement test of the dependent variable, the regression coefficient of ESG disclosure on total factor productivity (TFP) in the previous period was 0.003, and it was significantly positive at the 1% level. By replacing the explanatory variable, the ESG rating from Huazheng ESG was significantly positive at the 1% level when applied to the total factor productivity calculated using the LP method, validating the robustness of the conclusion.

(2) The regression coefficients for ESG ratings and technological innovation levels are 0.001, respectively, both positive and significant at the 1% confidence level, indicating that a company's ESG performance has a positive impact on its innovation level. Additionally, improvements in a company's ESG performance can enhance its technological innovation level, thereby increasing its total factor productivity. ESG and financing constraints are significantly negatively correlated at the 1% level, with a coefficient of -0.317, meaning that good ESG performance can effectively reduce financing constraints for firms. Firms can significantly alleviate financing constraints by improving their ESG levels through ESG governance, thereby enhancing their TFP levels.

(3) The regression coefficient between digital transformation and TFP is 0.021, and it is positive at the 1% confidence level. The regression coefficient for the interaction term between ESG performance and TFP is 0.019, and it is significant at the 1% level. That is, the higher a company's digital transformation, the stronger the positive impact of ESG performance on its TFP.

(4) A company's previous environmental performance has a U-shaped relationship with TFP, while social and governance performance have a linear positive impact.

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