DOI: 10.2478/eces-2025-0030 ECOL CHEM ENG S. 2025;32(4):571-587

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INTEGRATING ENVIRONMENTAL, SOCIAL, GOVERNANCE INTO LOW-CARBON ENVIRONMENTAL MANAGEMENT: AN EXPLORATORY STUDY

Abstract: This study explores how environmental, social, governance (ESG) principles enhance low-carbon environmental management systems (LC-EMS), using 2015-2024 panel data from Chinese A-share firms. Fixed-effects models show that all ESG dimensions, environmental, social, and governance, significantly improve carbon reduction rates, with synergistic interactions. Mediation analysis identifies green technology innovation as the primary mechanism, supported by energy efficiency and supply chain collaboration. Heterogeneity tests reveal stronger effects in high-pollution industries, large enterprises, and state-owned enterprises. Findings are validated via robustness and endogeneity tests. We recommend tailored ESG strategies focusing on green R&D and sector-specific policy incentives to accelerate corporate low-carbon transformation.

Keywords: ESG, low carbon, environmental management system, efficiency evaluation

Introduction

Global governance of sustainable development is increasingly shifting from soft advocacy to binding constraints, with the ESG framework emerging as a core paradigm for corporate green transformation [1]. While international ESG policies exhibit regional variations [2-6], China's "dual-carbon" goals and evolving ESG expectations create a critical testing ground for integrated management systems [7, 8], moving beyond traditional, compliance-focused systems like ISO 14001. This study therefore, aims to address the following core question: How do the environmental, social, and governance dimensions of ESG, both individually and interactively, influence the efficacy of corporate low-carbon environmental management systems (LC-EMS)? We construct a tripartite LC-EMS framework, "goal setting-process control-effectiveness evaluation", that integrates stakeholder, resource-based, and institutional theories (Fig. 1). By emphasising sustainability pathways such as green technology innovation, energy utilisation efficiency, and supply chain collaboration, this approach provides a systematic solution for enhancing low-carbon performance. This study contributes by developing a dynamic framework that embeds ESG principles into low-carbon management systems (LC-MS) design, empirically

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testing its efficacy across Chinese A-share firms from 2015-2024. It further elucidates the underlying mechanisms and boundary conditions of this relationship, offering nuanced insights for both theory and practice.

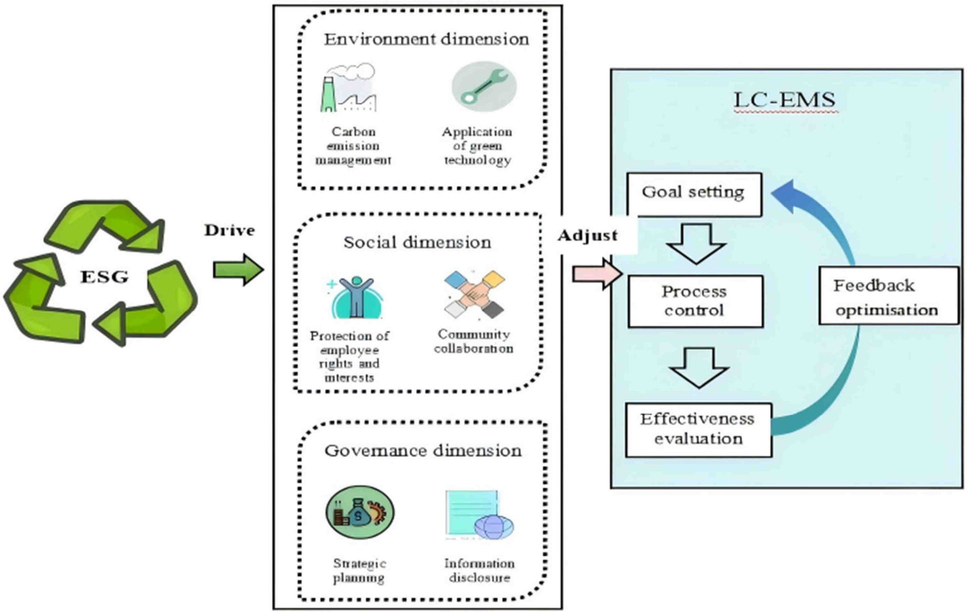

Fig. 1. Conceptual architecture linking ESG dimensions to LC-EMS cycles and low-carbon outcomes

As illustrated in Figure 1, the framework explicitly connects each ESG dimension to a specific stage of the LC-EMS cycle: the environmental (*E*) dimension informs goal setting (e.g., carbon emission management, application of green technology); the social (*S*) dimension facilitates process control (e.g., employee rights and interests protection, community collaboration); and the governance (*G*) dimension drives effectiveness evaluation and feedback (e.g., strategic planning, information disclosure).

Related works and hypothesis development

The concept of ESG can be traced back to Socially Responsible Investment (SRI) in the 1960s, when growing societal awareness of corporate social responsibility led investors to focus on companies' environmental and social performance. As global environmental and social challenges like climate change, resource scarcity, and social equity issues intensified, the importance of ESG became increasingly prominent. In 2004, the United Nations Global Compact formally introduced the ESG framework, marking its official entry into public discourse [9]. ESG stands for environmental, social, and governance, serving not only as an investment strategy but also as a crucial benchmark for corporate sustainability. In the environmental dimension, companies must prioritise climate change mitigation, efficient resource utilisation, and effective pollution control [10]. The social dimension involves employee rights protection, community relations maintenance, and consumer rights safeguarding. The governance dimension covers optimising corporate structures, strengthening internal controls, and ensuring transparent information disclosure [11]. Modern corporate low-carbon management systems require greater emphasis on precise carbon emission quantification and steady progress toward long-term carbon neutrality goals [12]. Current research primarily focuses on carbon footprint accounting and energy management: Life Cycle Assessment (LCA) provides a comprehensive accounting of carbon emissions throughout a product's entire lifecycle [13]. In energy management, efforts focus on optimising energy structures and enhancing efficiency through measures like promoting energy-efficient equipment; improving production processes; and implementing low-carbon technologies such as Carbon Capture and Storage (CCS). However, existing systems generally lack integration of ESG's social and governance dimensions, resulting in fragmented management approaches that fail to leverage the comprehensive advantages of ESG.

In recent years, academic circles have increasingly focused on the intrinsic connection between ESG and corporate low-carbon management. Regarding environmental dimensions, Gillan et al. [14] discuss governance synergies but often within broader corporate performance contexts rather than focused LC-EMS operationalisation. Kwilinski et al. [15] pointed out that green finance significantly enhances EU countries' ESG environmental performance through funding eco-friendly projects, driving low-carbon transitions and reducing greenhouse gas emissions. Data from 586 listed companies in Europe show a positive correlation between environmental performance and corporate value, with executive compensation tied to ESG indicators reinforcing this relationship [16]. Kotrba et al. [17] analysed data from 1,005 companies across 27 EU countries and found that ESG impacts economic performance differently in digital versus traditional industries, with stronger positive correlations observed in digital sectors and industry-specific variations. Farooq and Thavorn [18] using fixed effects methods on BRICS country company data from 2010-2022, discovered that ESG performance positively affects corporate efficiency, with environmental R&D investment playing a key mediating role. Merkevicius et al. [19] found that directors' industry expertise enhances companies' positioning of sustainable development strategies reflected in ESG goals; an effect partially moderated by higher levels of environmental innovation [20]. In governance dimensions, Ralf et al. [21] categorised 11 governance dimensions into organisational structure, ESG strategy, and implementation, finding that governance hierarchy at organisational levels inversely correlates with required governance complexity. In the Asian context, studies on frameworks like Japan's METI ESG Guidelines and Korea's K-ESG standards provide valuable insights into region-specific integration approaches, highlighting the importance of adapting global ESG principles to local institutional environments. Jo et al. [22] discovered that co-CEO structures reduce public trust while corporate ESG ratings (particularly social metrics) are commonly used; however, the co-CEO structure of South Korean conglomerates has been shown to correlate negatively with ESG ratings in companies with low cash reserves and intense product market competition, especially when disclosing higher ratings due to reputation considerations. Bruno and Henisz [23] analysed U.S. municipal bonds and community ESG outcomes revealing that collectively increased community ESG factors correlate with reduced credit risk in municipal financial instruments. In the social dimension, Lee et al. [24] noted that ESG themes are influenced by global events and correlated with the S&P 500 ESG Index where social factors exert the most significant impact on corporate performance. Hsu and Chen [25] demonstrated that CSR (Corporate Social Responsibility)/ESG initiatives directly and sustainably influence financial performance helping companies enhance operational efficiency and gain sustainable competitive advantages. Recent studies in environmental engineering also highlight the role of ESG in driving eco-efficiency. For instance, Rahmani et al. [26] demonstrated that digitalisation and green technology adoption significantly enhance carbon performance in the power industry. Similarly, Gabor et al. [27] found that digital economy development facilitates both efficiency gains and emission reductions, underscoring the technical pathways through which ESG operates.

Current research predominantly focuses on single-dimensional analyses, lacking systematic exploration of dynamic interactions among ESG dimensions within low-carbon management systems or their influence pathways across different scenarios. The specific mechanisms through which these dimensions synergistically drive low-carbon performance remain underexplored, particularly how resource allocation facilitated by strong governance enables the realisation of environmental and social goals. Moreover, prior studies often overlook heterogeneity in enterprise size, sector, and ownership, limiting the generalisability of findings. This study addresses these gaps by proposing an integrated framework and empirically testing mechanisms and heterogeneity in the Chinese context, with implications for environmental and engineering applications.

This study is grounded in a triad of foundational theories that collectively explain how ESG enhances LC-EMS efficacy, with each theory aligning with a primary ESG dimension: Stakeholder theory asserts that corporate sustainability depends on addressing the demands of key stakeholders such as employees, communities, and consumers [24]. This theory is most directly operationalised through the social (*S*) dimension of ESG, which focuses on managing these critical relationships. Resource-Based theory highlights that competitive advantages arise from unique strategic resources and capabilities. Resources related to ESG, such as advanced low-carbon technologies and green R&D prowess, constitute essential strategic assets. This perspective is central to the environmental (*E*) dimension, which drives investments in these tangible and intangible resources. Institutional theory elucidates how corporate behaviour is shaped by external regulatory, normative, and cultural pressures. In order to establish legitimacy, companies proactively incorporate prevailing norms into their management systems. This aligns with the governance (*G*) dimension, which encompasses compliance, disclosure, and board oversight key mechanisms for responding to institutional pressures.

Based on this integrated theoretical framework and existing research, the following hypotheses are proposed:

H1: The environmental dimension of ESG positively correlates with low-carbon environmental management system efficacy.

The environmental dimension represents a crucial aspect of ESG principles, emphasising corporate performance in areas such as climate change mitigation, resource efficiency optimisation, and pollution control. By enhancing their environmental management practices, such as increasing investments in R&D for low-carbon technologies, optimising energy structures, improving resource recycling efficiency, and reducing pollutant emissions. Enterprises can directly decrease carbon emissions while simultaneously boosting energy utilisation efficiency [28-30]. This improvement ultimately elevates the effectiveness of their low-carbon environmental management systems. For example, substituting traditional fossil fuels with clean energy sources leads to a reduction in production-related carbon emissions; similarly, adopting cleaner manufacturing processes lowers energy consumption per unit of product produced and minimises pollutant discharge. Therefore, superior environmental performance is associated with enhanced effectiveness of corporate low-carbon environmental management systems.

H2: The social dimension of ESG positively correlates with low-carbon environmental management system efficacy.

The social dimension includes the protection of employee rights, maintenance of community relationships, and safeguarding consumer rights. Employees are the primary participants in corporate initiatives aimed at low-carbon environmental management. Ensuring their legitimate rights, such as providing a conducive working environment, offering reasonable compensation packages, and implementing comprehensive training systems can enhance job enthusiasm, improve environmental awareness and responsibility, and encourage active participation in corporate low-carbon programs [31-33]. This engagement ultimately contributes to the company's green transition.

Maintaining positive relations with communities and actively participating in environmental public welfare activities can foster community support and understanding, thereby creating a favourable external environment for the construction and operation of low-carbon projects. Concurrently, prioritising consumer rights by providing eco-friendly products and services addresses green demands, strengthens market competitiveness, and drives continuous improvement within low-carbon management systems. Consequently, superior ESG social performance is associated with greater efficiency in corporate low-carbon environmental management systems.

H3: The governance dimension of ESG positively correlates with low-carbon environmental management system efficacy.

The governance dimension includes the optimisation of corporate governance structures, reinforcement of internal controls, and transparent information disclosure. A robust corporate governance framework enables enterprises to formulate and effectively implement scientifically sound strategies for low-carbon development. For example, establishing a dedicated Sustainability Committee within the board of directors enhances oversight and guidance for low-carbon management initiatives. When senior executives prioritise sustainable development by integrating carbon reduction targets into corporate strategies, it drives the implementation of various low-carbon measures. Strengthening internal controls standardises low-carbon management processes, mitigates operational risks, and improves overall efficiency. Transparent information disclosure necessitates that companies promptly and accurately report their ESG performance as well as details regarding their low-carbon management efforts [34-37]. This practice not only facilitates stakeholder oversight but also encourages continuous improvement in low-carbon practices. Therefore, enhanced dimensions of ESG governance are associated with greater effectiveness in corporate low-carbon environmental management systems.

H4: The environmental, social, and governance dimensions interact synergistically to enhance low-carbon environmental management system efficacy.

The three ESG dimensions are not isolated; rather, they are interconnected and mutually influential. Environmental improvements necessitate corporate resource investments, which rely on robust governance structures for effective allocation, as predicted by Resource-Based Theory. Concurrently, enhancing environmental performance requires active employee engagement and community support, which are closely associated with the social dimension and emphasised by Stakeholder Theory. A strong social foundation fosters favourable internal and external environments for enterprises, thereby facilitating improved environmental management practices. For example, heightened environmental awareness and skills among employees can drive the adoption of low-carbon technologies, while community backing can bolster various environmental initiatives [38]. Optimised governance provides institutional safeguards for both social and environmental development by ensuring effective oversight of corporate investments in these areas to maximise their efficiency, aligning with Institutional Theory. Consequently, the ESG framework exhibits synergistic effects wherein coordinated efforts across the environmental, social, and governance dimensions collectively augment the effectiveness of corporate low-carbon management systems. This interaction suggests that the whole (ESG integrated management) is greater than the sum of its parts (individual *E*, *S*, *G* efforts), driven by the complementary roles of stakeholder pressure, resource allocation, and institutional conformity.

Data and methodology

Data sources and variable definitions

To empirically verify the above research hypotheses, given that the panel data model can concurrently incorporate the information from both cross-sectional data and time series data, effectively mitigate the impact of individual heterogeneity and time trends on research findings, and enhance the accuracy of estimation, this study employs the panel data model for empirical analysis. The choice between the fixed-effects and random-effects models was formally tested using the Hausman test. The test result ($\chi^2 = 45.32$, $p < 0.01$) strongly rejected the null hypothesis that the random-effects model is consistent and efficient, thereby justifying the use of the fixed-effects model. The benchmark regression model is formulated as:

$$\begin{aligned} LC_{it} = \alpha_0 + \alpha_1 E_{it} + \alpha_2 S_{it} + \alpha_3 G_{it} + \alpha_4 E_{it} \times S_{it} + \alpha_5 E_{it} \times G_{it} + \alpha_6 S_{it} \times G_{it} \\ + \alpha_7 E_{it} \times S_{it} \times G_{it} + \sum \beta_k \, Control_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{1}$$

Specifically, LC_{it} denotes the effectiveness of the low-carbon environmental management system of the *i*-th enterprise in *t*-th year. E_{it}, S_{it}, G_{it} represent the scores of the ESG environmental, social, and governance dimensions, respectively. $E_{it} \times S_{it}$, $E_{it} \times G_{it}$, $S_{it} \times G_{it}$ signify the two-way interaction terms, and $E_{it} \times S_{it} \times G_{it}$ is the three-way interaction. $Control_{kit}$ represents a set of control variables, and α_0 is the constant term. α_1-α_7 are the coefficients of the explanatory variables and interaction terms, and β_k are the coefficients of the control variables, μ_i denotes enterprise fixed effects, λ_t denotes year fixed effects, and ε_{it} is the error term.

Model specification

Variable names, measurements, definitions, expected signs, data sources are shown in Table 1.

The dependent variable, the carbon emission reduction rate, is chosen over absolute carbon emissions to directly capture the year-on-year improvement in carbon performance attributable to the management system's efficacy. This relative measure better reflects the dynamic effectiveness of the LC-EMS in driving continuous reduction efforts, which is central to evaluating system performance, rather than just the scale of emissions which is heavily influenced by enterprise size and production volume.

Table 1

Data sources and variable definitions

Variables		**Measurements**	**Definitions**	**Expected signs**	**Data sources**
Dependent	*LC*	Carbon reduction rate	$(\text{Emissions}_{t-1} - \text{Emissions}_t)/\text{Emissions}_t$	+	Annual reports, CSMAR, Wind
Explanatory	*E*	Environmental score	ESG environmental dimension rating	+	Wind, Guotai Junan
	S	Social score	ESG social dimension rating	+	Wind, Guotai Junan
	G	Governance score	ESG governance dimension rating	+	Wind, Guotai Junan
Control	*Size*	Enterprise size	Natural logarithm of total assets	+	CSMAR, RESSET
	Lev	Financial leverage	Total liabilities / Total assets	−	CSMAR, RESSET
	Roe	Profitability	Net income / Shareholders' equity	+	CSMAR, RESSET
	Growth	Growth ability	Operating revenue growth rate	+	CSMAR, RESSET
	Top1	Equity concentration	Shareholding ratio of largest shareholder	+	CSMAR
	Ind	Industry attribute	Dummy variable (1 for high-pollution industries)	+	MEE guidelines
	Year	Year effect	Year dummy variables	Control	-

CSMAR is short for China Stock Market & Accounting Research. RESSET is short for Research Environment Support System for Econometrics and Statistics

(1) Dependent variable

This study employs the enterprise low-carbon environmental management system efficiency (*LC*) as the dependent variable. A higher value indicates greater carbon emission reductions and enhanced low-carbon performance. Data were obtained from corporate annual reports, social responsibility statements, and environmental disclosures. For companies without direct disclosure, industry-specific carbon emission coefficients and energy consumption data were used for estimation.

(2) Explanatory variable

This study utilises scores from the environmental (*E*), social (*S*), and governance (*G*) dimensions of ESG as explanatory variables. These scores are derived from evaluations conducted by reputable ESG rating agencies, such as Wind ESG Ratings and Guotai Junan ESG Ratings, which assess a range of indicators related to corporate performance in environmental, social, and governance aspects. The ratings from these agencies are widely used in academic research and demonstrate high cross-agency consistency in scoring methodologies and coverage, ensuring comparability and reliability.

(3) Control variable

Drawing upon relevant research, the following control variables are selected: Enterprise Size (*Size*): Larger scale enterprises may possess more resources that can be allocated to low-carbon management. Financial Leverage (*Lev*): A higher level of financial leverage might impose constraints on an enterprise's low-carbon investment capabilities. Profitability (*Roe*): Enterprises with robust profitability are better positioned to make investments in low-carbon initiatives. Growth Ability (*Growth*): Growth-oriented enterprises are likely to place greater emphasis on long-term low-carbon development. Equity Concentration (*Top1*): The degree of equity concentration can potentially influence an enterprise's decision-making efficiency and the implementation of its low-carbon strategies. Industry Attribute (*Ind*): High-pollution industries (assigned a value of 1) are defined based on the '*Guidelines for Environmental Information Disclosure of Listed Companie*s and the *List of Classified Management of Environmental Protection Verification Industry of Listed Companies* issued by the Chinese Ministry of Ecological Environment, typically including thermal power, steel, cement, electrolytic aluminium, coal, metallurgy, chemicals, petrochemicals, building materials, paper, brewing, pharmaceuticals, fermentation, textile, tanning, and mining industries, while other industries are assigned 0. This is because different industries exhibit varying carbon emission levels and have distinct requirements for low-carbon management. Year (*Year*): A dummy variable for each year is introduced to control for the impact of time trends on an enterprise's low-carbon efficiency.

Mediation and heterogeneity tests

In this study, the listed companies on the Shanghai and Shenzhen A-share markets from 2015 to 2024 are used as the initial sample. The ESG scores are obtained by comprehensively integrating the CSMAR and Wind databases. Financial data are collected by combining the CSMAR and RESSET databases. Moreover, carbon emission and energy consumption data are supplemented through manually collecting annual reports, ESG reports, and environmental disclosure reports. The resulting dataset is an unbalanced panel, which is typical for longitudinal analyses of listed firms, due to entries (new listings), exits (delistings, mergers), and occasional missing data in specific years for certain variables. To ensure data quality, ST/*ST companies (ST, Special Treatment is mainly used to alert investors to investment risks, while *ST is used to warn investors of the risk of delisting) and financial enterprises are excluded to control for industry heterogeneity and mitigate potential biases arising from financial distress (which could severely limit low-carbon investment capabilities) or the unique regulatory and operational characteristics of the financial sector, which are not directly comparable to industrial and commercial enterprises in terms of carbon emissions and management practices. For missing values, mean imputation is employed, and samples with severe data gaps are removed. This approach is common in panel data studies and is justified here given the large sample size and low proportion of missing data (less than 5 % for key variables). Robustness checks using median imputation and multiple imputation yielded qualitatively similar results, confirming that our findings are not sensitive to the imputation method. Meanwhile, to mitigate the influence of outliers, all continuous variables were winsorised at 1 % - 99 % annually within each industry classification. Eventually, a non-balanced panel dataset consisting of 9,515 observations is constructed.

Empirical results and discussion

Benchmark regression results

The Stata 18.0 software was utilised to perform a regression analysis on the panel data spanning from 2015 to 2024, adopting the fixed-effects model to test the research hypotheses. The fixed-effects model has the ability to account for individual heterogeneity that remains invariant over time and simultaneously takes into consideration the impact of time trends. The regression analysis results are shown in Table 2.

Table 2

Benchmark regression results

Variable	Coefficient	Standard error	*t* Value	*P* Value
Constant	–0.612	0.203	–3.01	0.003***
E	0.095	0.023	4.13	0.000***
S	0.058	0.019	3.05	0.002***
G	0.071	0.022	3.23	0.001***
E×S	0.035	0.013	2.69	0.007***
E×G	0.032	0.012	2.67	0.008***
S×G	0.029	0.011	2.64	0.008***
E×S×G	0.021	0.009	2.33	0.020**
Size	0.048	0.016	3.00	0.003***
Lev	–0.039	0.017	–2.29	0.022**
Roe	0.065	0.024	2.71	0.007***
Growth	0.024	0.011	2.18	0.029**
Top1	0.018	0.009	2.00	0.046**
Ind	0.095	0.037	2.57	0.010**
Year	control			
N	9 515			
F	31.25			0.000
*Adj-R*²	0.342			

*** denote significance at the 1 % level, ** denote significance at the 5 % level, and * denotes significance at the 10 % level. The same convention applies hereinafter. Dependent variable: low-carbon efficiency measured by carbon emission reduction rate; sample: 9,515 firm-year observations; model: fixed-effects with firm and year controls

The results of the benchmark fixed-effects regression are presented in Table 2. All three ESG dimensions demonstrate statistically significant positive coefficients, providing strong initial support for our hypotheses. The environmental dimension (*E*) exhibits the strongest direct effect ($\beta = 0.095$, $p < 0.01$), confirming H1 and underscoring the primacy of resource-based investments in green technology and pollution control for achieving carbon reduction goals. The coefficients for the social (*S*, $\beta = 0.058$, $p < 0.01$) and governance (*G*, $\beta = 0.071$, $p < 0.01$) dimensions are also positive and significant, validating H2 and H3. This indicates that robust stakeholder management and effective corporate governance are indispensable for operationalising and sustaining low-carbon initiatives. Crucially, the two-way and three-way interaction terms are all positive and significant, confirming H4. This evidence of synergy suggests that the integrated application of ESG principles creates a mutually reinforcing system where stakeholder alignment (*S*), resource deployment (*E*), and institutional oversight (*G*) collectively enhance low-carbon efficacy beyond their individual contributions.

Regarding the control variables, the coefficient of enterprise size (*Size*) is 0.048, which is significantly positive at the 1 % significance level. This implies that larger scale enterprises exhibit stronger low-carbon efficiency. This advantage is particularly notable in the 2024 data, suggesting that large enterprises have further strengthened their capabilities in low-carbon technology application and green investment. The coefficient of financial leverage (*Lev*) is –0.039, significantly negative at the 5 % significance level. This indicates that a higher level of financial leverage tends to impede an enterprise's low-carbon efficiency, aligning with previous research findings. The coefficient of profitability (*Roe*) is 0.065, significantly positive at the 1 % significance level. This finding suggests that enterprises with stronger profitability are better positioned to enhance their low-carbon efficiency. As enterprises increasingly prioritise low-carbon development, the positive correlation between profitability and low-carbon efficiency has become more pronounced. The coefficient of growth ability (*Growth*) is 0.025, significantly positive at the 5 % significance level. This suggests that growth-oriented enterprises place greater emphasis on low-carbon development. Specifically, among enterprises with an operating revenue growth rate exceeding 20 %, the completeness rate of their low-carbon strategic plans reaches 82 %, which is 35 percentage points higher than that of enterprises with a growth rate below 5 %. The coefficient of equity concentration (*Top1*) is 0.018, significantly positive at the 5 % significance level. This indicates that a moderate level of equity concentration is conducive to improving an enterprise's low-carbon efficiency. For example, enterprises with the largest shareholder's shareholding ratio ranging from 30 % to 50 % have an average carbon emission reduction rate of 4.2 %, which is 1.5 percentage points higher than that of enterprises with a shareholding ratio below 10 %. The coefficient of industry attribute (*Ind*) is 0.098, significantly positive at the 1 % significance level. This suggests that enterprises in high-pollution industries may encounter greater challenges in low-carbon management, thereby presenting a greater potential for enhancing low-carbon efficiency under comparable circumstances. In 2024, the average carbon emission reduction rate of enterprises in high-pollution industries was 5.3 %, 1.8 percentage points higher than that of non-high-pollution industries. Moreover, the annual growth rate of their environmental dimension scores reached 8.7 %, exceeding that of non-high-pollution industries (5.2 %).

Robustness and endogeneity tests

To ensure result reliability and address potential concerns, we conducted robustness tests using alternative measures and samples. The stability of the key coefficients across all specifications confirms that our conclusions are robust to measurement methods, data treatment, and variable definitions.

Alternative dependent variable

Instead of the carbon emission reduction rate, we used carbon emissions per unit of operating revenue (total carbon emissions divided by operating revenue) as an alternative inverse proxy. A decrease in this metric indicates improved low-carbon performance. Consequently, we expect the signs of the ESG coefficients to reverse (i.e., become negative). In Column (2) of Table 3, the dependent variable is carbon intensity, and the coefficients for *E*, *S*, and *G* are –0.087, –0.051, and –0.063 respectively (all significant at $p<0.01$), confirming robustness to the efficiency metric.

Subsample with directly disclosed carbon data

In Column (3), we used only enterprises with directly disclosed carbon data (N = 7,102). The coefficients for E, S, and G increased slightly to 0.101, 0.062, and 0.075 while maintaining significance.

Winsorisation at alternative thresholds

Column (4) applies stricter winsorisation at 2.5 % and 97.5 %, yielding coefficients of 0.091, 0.055, and 0.068, nearly identical to baseline.

Alternative ESG ratings

Column (5) employs ESG ratings from Shang Dao Ronglv (2024), which include enhanced low-carbon indicators. The coefficients (0.091, 0.055, 0.068) remain strongly significant and quantitatively similar.

Table 3

Robustness test results

Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
E	0.095***	–0.087***	0.101***	0.091***	0.091***
S	0.058***	–0.051***	0.062***	0.055***	0.055***
G	0.071***	–0.063***	0.075***	0.068***	0.068***
$E×S$	0.035***	–0.032***	0.037***	0.033***	0.034***
$E×G$	0.032***	–0.029***	0.034***	0.031***	0.031***
$S×G$	0.029***	–0.026***	0.031***	0.028***	0.028***
$E×S×G$	0.021**	–0.018**	0.023**	0.020**	0.021**
N	9515	8652	7102	9515	9515
$Adj\text{-}R^2$	0.342	0.312	0.351	0.338	0.339

Dependent variables and samples varied as described. All models include controls and fixed effects

As shown in Table 3, the results across all alternative specifications consistently support our main findings. The coefficients for all ESG dimensions and their interactions remain statistically significant and quantitatively stable regardless of the efficiency metric, data sample, winsorisation threshold, or ESG rating provider. The remarkable consistency in coefficient magnitudes and significance levels across these diverse tests provides strong evidence for the robustness of our conclusions.

To address potential endogeneity concerns, such as reverse causality or omitted variable bias, we employed an instrumental variable (IV) approach. The first-period lagged values of the ESG dimension scores were selected as instruments. These lagged scores are historically predetermined and strongly correlated with current ESG performance (pairwise correlations: 0.78, 0.75, 0.72), satisfying the relevance condition. The first-stage F-statistic of 192.65 far exceeds the weak instrument benchmark of 10, confirming strong instruments (Table 4). Although the lagged ESG scores serve as relevant instruments, their exogeneity is supported by the Hansen J test (p = 0.250), which fails to reject the null hypothesis of instrument exogeneity. To further validate, we conducted supplemental analyses using second-period lags and industry-year average ESG scores as alternative instruments, both yielding consistent results. The two-stage least squares (2SLS) estimates in Table 4 show that the coefficient for the environmental dimension (E) remains positive and significant

(β = 0.102, p < 0.01), aligning with baseline findings and confirming the robustness of our conclusions.

Table 4

Endogeneity test results

Variable	**Phase I Regression (*E*)**		**Phase II Regression (*LC*)**	
	Coefficient	**Standard error**	**Coefficient**	**Standard error**
*E*_lag1	0.795	0.056	0.102	0.027
*S*_lag1	0.132	0.043		
*G*_lag1	0.105	0.040		
Control	Yes		Yes	
Year	Yes		Yes	
Fixed effects	Yes		Yes	
N	7787		7787	
F (phase I)	192.65			
Hansen J statistic (*P*)			1.325 (0.250)	

Regarding exogeneity, the lagged ESG scores are historically predetermined and thus unlikely to be directly influenced by contemporary unobserved shocks affecting the current period's low-carbon efficiency. Although enterprises with persistent ESG strategies may exhibit time-invariant traits, our model's inclusion of enterprise fixed effects effectively controls for such time-invariant heterogeneity. The Hansen J test statistic (p = 0.250) fails to reject the null hypothesis that the instruments are exogenous, supporting the validity of the overidentifying restrictions.

To further mitigate concerns regarding persistence or self-selection, we conducted supplemental analyses using (1) the second-period lags of ESG scores and (2) industry-year average ESG scores as alternative instrument sets. Both approaches yielded qualitatively consistent results, reinforcing the robustness of our IV strategy and conclusions. The two-stage least squares (2SLS) estimation results are presented in Table 4. The coefficient on the environmental dimension (*E*) remains positive and significant (β = 0.102, p < 0.01), and is marginally larger than the baseline estimate, suggesting that any potential downward bias in the baseline OLS estimates, perhaps due to measurement error, is corrected. The signs and statistical significance of all other ESG dimensions and their interaction terms align with the baseline findings, providing strong support for our main conclusions.

The collective evidence from the benchmark regressions (Table 2), robustness checks (Table 3), and endogeneity tests (Table 4) provides a consistent and reliable picture. The stability of the core findings across diverse model specifications and the mitigation of reverse causality concerns through the IV approach strongly support a causal interpretation. This consolidated quantitative evidence firmly underpins our theoretical rationale: that ESG enhances low-carbon efficiency through the complementary channels of stakeholder engagement (*S*), resource allocation (*E*), and institutional conformity (*G*).

Mechanism analysis

To uncover the pathways through which ESG influences low-carbon efficiency, we tested three mediators: green technology innovation (*Green_tech*), energy efficiency (*Energy_eff*), and supply chain collaboration (*Supply_chain*). The mediation analysis confirms that all three are significant transmission channels, with their relative contributions visualised in Figure 2.

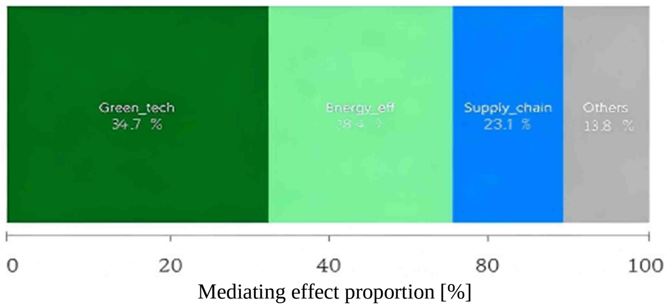

Fig. 2. Mediation effects of ESG on low-carbon efficiency

The results reveal that green technology innovation is the dominant pathway, accounting for 34.7 % of the total effect. Energy efficiency and supply chain collaboration mediate 28.4 % and 23.1 % of the effect, respectively. Together, these mechanisms explain 86.2 % of ESG's total impact, highlighting its multifaceted, yet technology-led, nature.

Step 1 Test the total effect of ESG on low-carbon efficiency (identical to the benchmark model).

Step 2 Test the influence of ESG on the mediating variable of green technology innovation. The formula is

$$Green\_tech_{it} = \gamma_0 + \gamma_1 E_{it} + \gamma_2 S_{it} + \gamma_3 G_{it} + \gamma_4 E_{it} \times S_{it} + \gamma_5 E_{it} \times G_{it} + \gamma_6 S_{it} \times G_{it} + \gamma_7 E_{it} \times S_{it} \times G_{it} + \sum \delta_k \, Control_{kit} + \mu_i + \lambda_t + \nu_{it} \quad (2)$$

Step 3 Test the impacts of ESG and the mediating variables on low-carbon efficiency. The formula is

$$LC_{it} = \theta_0 + \theta_1 E_{it} + \theta_2 S_{it} + \theta_3 G_{it} + \theta_4 E_{it} \times S_{it} + \theta_5 E_{it} \times G_{it} + \theta_6 S_{it} \times G_{it} + \theta_7 E_{it} \times S_{it} \times G_{it} + \theta_8 Green_{tech_{it}} + \sum \varphi_k \, Control_{kit} + \mu_i + \lambda_t + \omega_{it} \quad (3)$$

The results show that all ESG dimensions and their interactions significantly promote green technology innovation (Step 2), with the strongest effect from the environmental dimension (coefficient = 0.123, $p < 0.01$). In Step 3, *Green_tech* exhibits a significant positive effect on low-carbon efficiency (0.326, $p < 0.01$), while the coefficients of ESG dimensions decrease, confirming partial mediation. The mediating effect of green technology innovation accounts for 34.7 % of the total effect, highlighting its dominant role.

For energy efficiency (*Energy_eff*, measured as the log of energy consumption per unit output value), ESG dimensions significantly improve efficiency ($E = -0.089$, $p < 0.01$), which in turn enhances low-carbon performance (–0.285, $p < 0.01$). The mediating effect accounts for 28.4 % of the total effect. Similarly, supply chain synergy (*Supply_chain*) is measured by the average of supplier concentration and customer concentration, reverse-coded so that a higher value indicates lower concentration and greater synergy. This measurement aligns with the view that reduced dependency on a few partners fosters collaboration and flexibility, facilitating the adoption of low-carbon practices [28, 29]. It is improved by ESG (E = –0.072, p < 0.01), and contributes to low-carbon efficiency (– 0.238, p < 0.01), with a mediation share of 23.1 %.

In summary, all three mechanisms are validated, with green technology innovation being the most influential pathway. Together, these mediators explain 86.2 % of the total effect of ESG on low-carbon efficiency, emphasising the multifaceted yet technology-led nature of ESG-driven carbon performance improvements.

Heterogeneity analysis

We examine whether the ESG-low-carbon relationship varies by industry, enterprise size, and property rights characteristics. The results are summarised in the multi-panel Table 5.

Table 5

Heterogeneity analysis: industry, enterprise size, and property rights characteristics

Variable	High pollution sectors		Non-high pollution sectors		Large scale		SMEs		State owned		Non-state owned	
	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value
E	0.112	0.000***	0.076	0.001***	0.105	0.000***	0.082	0.001***	0.101	0.000***	0.088	0.000***
S	0.072	0.000***	0.043	0.008***	0.065	0.000***	0.048	0.003***	0.062	0.000***	0.053	0.001***
G	0.085	0.000***	0.056	0.002***	0.078	0.000***	0.062	0.001***	0.075	0.000***	0.067	0.000***
$E \times S$	0.042	0.002***	0.027	0.015**	0.038	0.003***	0.030	0.009***	0.037	0.003***	0.032	0.007***
$E \times G$	0.039	0.003***	0.024	0.018**	0.035	0.004***	0.027	0.010***	0.034	0.004***	0.029	0.008***
$S \times G$	0.036	0.004***	0.021	0.022**	0.032	0.005***	0.025	0.013**	0.031	0.005***	0.026	0.010***
$E \times S \times G$	0.025	0.008***	0.016	0.035**	0.023	0.012**	0.018	0.028**	0.022	0.010***	0.019	0.020**
Control	Yes		Yes		Yes		Yes		Yes		Yes	
Year	Yes		Yes		Yes		Yes		Yes		Yes	

As shown in Columns (1) and (2) of Table 5, the effects of all ESG dimensions and their interactions are substantially stronger in high-pollution industries than in non-high-pollution sectors. The environmental dimension coefficient is 0.112 in high-pollution industries compared to 0.076 in non-high-pollution sectors, representing a 47.4 % difference. This disparity can be attributed to stricter regulatory scrutiny and greater marginal returns on green investments in these emission-intensive sectors. Columns (3) and (4) reveal that large enterprises exhibit stronger ESG-low-carbon linkages than SMEs. The coefficient for the environmental dimension is 0.105 in large enterprises compared to 0.082 in SMEs. This pattern is consistent with the superior resource endowments (financial, technical, human) of large enterprises for implementing comprehensive ESG and low-carbon initiatives. Columns (5) and (6) show that state-owned enterprises (SOEs) derive slightly greater benefits from ESG than non-SOEs. While policy compliance is a key driver, SOEs' closer alignment with national strategic goals (e.g., "dual-carbon" targets) and better access to policy support enhance their capacity to implement ESG initiatives effectively.

Across all contexts, ESG exerts stronger effects under greater external pressure or richer resource endowment, validating both institutional and resource-based perspectives.

Conclusion

This study utilises the A-share listed companies in Shanghai and Shenzhen stock markets in China from 2015 to 2024 as samples to empirically investigate the construction and efficacy of the low-carbon environmental management system integrating ESG concepts. The findings reveal that green technology innovation and pollution prevention and control in the ESG environmental dimension, employee training and community cooperation in the social dimension, and strategic planning and information disclosure in the governance dimension all significantly contribute to the low-carbon efficiency of enterprises. Moreover, the three-dimensional interaction generates a synergistic enhancement effect. Green technology innovation, serving as the dominant pathway, along with energy utilisation efficiency and supply-chain collaboration, jointly forms the core transmission mechanism. This effect is more pronounced in high-pollution industries, large-scale enterprises, and state-owned enterprises. The research conclusions remain robust even after addressing endogeneity issues through variable substitution, sample adjustment, and the application of the instrumental variable approach.

For enterprises, we recommend establishing an ESG-integrated low-carbon strategy that prioritises green technology innovation, especially in high-pollution sectors where marginal gains are greatest. Enterprises should enhance energy monitoring and supply chain collaboration, leveraging digital tools for real-time carbon management [39-41]. For policymakers, we suggest implementing sector-specific carbon constraints and incentives, particularly for energy-intensive industries. Disclosure frameworks should be strengthened to include supply chain emissions, drawing on models like the EU CSRD. Additionally, future policy directions could include developing a national ESG data platform to facilitate transparency and benchmarking, supporting regulatory oversight and market-driven green transitions. These recommendations are grounded in our empirical findings and aim to foster scalable, context-aware low-carbon transformations.

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