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Unlocking corporate green governance capabilities in China: A supply chain-oriented evaluation based on an improved FBWM-CoCoSo method

Liying Yu[a], Xinli Kang[a] and Ran Qiu[a*]

[a]*School of Management, Shanghai University, Shanghai, 200444, China*

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A B S T R A C T

This study develops a framework consisting of normative, leadership, and sustainable capabilities to evaluate corporate green governance capabilities (CGGC) in supply chains. The Fuzzy Best-Worst Method (FBWM) is used to determine indicator weights, and the Combined Compromise Solution (CoCoSo) method is applied to rank firm performance in the Yangtze River Delta from 2014 to 2022. Results show low but improving governance levels with notable differences across regions and enterprise types. Leadership capabilities are more affected by external shocks. State-owned and high-pollution firms perform better, while non-state and labor-intensive firms improve more rapidly. The study contributes methodological and practical insights.

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1. Introduction

The increasing frequency and severity of extreme climate events have heightened global awareness of the necessity to balance economic development with environmental sustainability. Green governance has thus emerged as a strategic imperative for enterprises, enabling efficient resource utilization and long-term ecological improvements through proactive, participatory, and systematic management (Li et al., 2018). As primary contributors to resource consumption and pollution emissions, enterprises play a pivotal role in green governance. This governance extends across multiple domains, including risk management, corporate culture, finance, production, and procurement. By leveraging managerial innovation, energy efficiency, emissions reduction, and clean technology, enterprises must reconcile economic interests with ecological sustainability (Yao et al., 2022). However, many enterprises exhibit limited intrinsic motivation to actively pursue green governance due to its high externalities and the lack of immediate economic returns (Van Beurden & Gossling, 2008). A systematic evaluation of corporate green governance capabilities (CGGC) can help enterprises assess their current standing and formulate clear improvement strategies. Nevertheless, existing research primarily focuses on environmental performance (Nguyen et al., 2021), often neglecting the broader and more intricate concept of green governance (Lin et al., 2019). Although ESG criteria incorporates governance-related variables, they frequently treat green initiatives and governance as distinct components rather than as an integrated whole (Li et al., 2021). Therefore, a comprehensive evaluation framework for CGGC is essential to identify pathways for enhancing governance effectiveness. Notably, enterprises operate within increasingly interconnected supply chain networks, engaging in complex business transactions and financial exchanges (Bak et al., 2020). A single enterprise's green governance actions can significantly impact the sustainability of the entire supply chain, necessitating coordinated efforts across all entities. From the supply chain perspective, implementing integrated green management strategies is crucial for securing long-term competitive advantages (Koberg & Longoni 2019). Therefore, incorporating the supply chain perspective into CGGC evaluations is imperative to comprehensively assess governance

* Corresponding author
E-mail qiuran@shu.edu.cn (R. Qiu)
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effectiveness within this interdependent context. The Yangtze River Delta (YRD) is a key economic hub in China, exerting substantial influence on national economic development (Wang et al., 2022). As core drivers of regional economic activity, enterprises in the YRD play a critical role in supply chain governance and regional green transformation. Evaluating CGGC in this region can elucidate enterprises' contributions to sustainable development while offering theoretical insights and practical guidance for broader policy formulation and capability-building initiatives.

Based on the above analysis, the key issues this paper aims to address are as follows:
(1) How can CGGC be conceptualized from the supply chain perspective and systematically developed into a comprehensive evaluation framework?
(2) How can the efficiency and accuracy of CGGC evaluation be optimized?
(3) How can CGGC be empirically evaluated in the YRD? Specifically, what is its current state, and what strategies can enhance these capabilities?

To address these issues, this study constructs a three-dimensional evaluation framework encompassing normative, leadership, and sustainable capabilities. The framework employs a Fuzzy Best-Worst Method (FBWM) and Combined Compromise Solution (CoCoSo) approach to assess the dynamic evolution of CGGC in the YRD. Additionally, this study explores CGGC heterogeneity from the perspectives of ownership structure, industry characteristics, and enterprise lifecycle.

The marginal contributions of this paper are as follows:

(1) Existing literature on CGGC evaluation has rarely adopted a multidimensional evaluation framework (Barnes et al., 2016; Yuan et al., 2018), focusing predominantly on internal corporate capabilities. This paper extends the conceptualization of CGGC by highlighting three features: governance entity, governance environment, and governance lifecycle. A multidimensional evaluation framework is then developed from the supply chain perspective, incorporating three dimensions—normative, leadership, and sustainable capabilities. This framework enhances understanding of how enterprises integrate internal resources, exert influence within complex supply chains, and sustain long-term governance efforts.

(2) Existing literature mainly focuses on environmental performance evaluations, typically using traditional quantitative methods such as Entropy-weight TOPSIS (Dos Santos et al., 2019), Data Envelopment Analysis (DEA) (Matsumoto et al., 2020) and its derivatives (Chen et al., 2021), as well as the Analytic Hierarchy Process (AHP) (Meng and Shaikh 2023). This paper proposes a refined evaluation model for CGGC, integrating the improved FBWM and CoCoSo methods. Specifically, the improved FBWM is employed to determine indicator weights, while the CoCoSo is applied to calculate the comprehensive evaluation value. This model not only enhances decision-making efficiency but also better accommodates scenarios involving incomplete information or ambiguous decisions.

(3) Existing literature on CGGC evaluation often overlooks inter-enterprise heterogeneity, predominantly focusing on governance levels at specific points in time, with limited investigation into their longitudinal trends (Zhang & Guo 2022). Drawing on a comprehensive evaluation of CGGC in the YRD from 2014 to 2022, this paper uncovers the evolving governance patterns, analyzing CGGC across different ownership structures, industry characteristics, and enterprise lifecycle stages. The findings offer valuable theoretical insights for the development and refinement of corporate green governance policies.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 establishes the relevant conceptual framework. Section 4 outlines the research methodology. Section 5 analyzes the results and conducts further discussion. Section 6 provides theoretical and practical implications. Section 7 presents limitations and prospects. Section 8 summarizes the research conclusions.

2. Literature review

The concept of green governance originated from the Western environmental movement and has evolved over time in response to societal changes, gradually becoming a global consensus and action. Initially, scholars focused solely on the concepts of "green" or "governance". One perspective argues that the essence of green governance lies in utilizing "governance" mechanisms to influence an organization's green practices (Padilha & Verschoore 2013), while another perspective defines green governance from a "green" viewpoint, considering it as measures taken to achieve environmental greening (Kuo et al., 2015). Subsequently, the two complex concepts, "green" and "governance", began to be systematically linked. Increasingly, scholars have viewed green governance as a "public affair activity" that involves the participation of governance entities, implementation of governance measures, and coordination of governance mechanisms (Li et al., 2017). In modern society, corporate social responsibility has gained significant attention, with enterprises gradually becoming the focal point of green governance research. Existing studies indicate that enterprise green governance contributes to improving organizational performance (Kuo et al., 2015), financial performance (Miroshnychenko et al., 2017), and environmental performance (Ahmed et al., 2021). However, although some scholars have made preliminary definitions of enterprise green governance, a consensus has yet to be reached (Lin & Chen, 2017; Zhang & Guo, 2022). Overall, enterprise green governance has evolved

from being primarily reliant on mandatory environmental regulations to a self-directed green behavior embedded within corporate governance structures. Thus, the drivers of enterprise green governance can be categorized and analyzed from both external and internal perspectives.

External driving factors primarily stem from the pressures exerted by various stakeholders, including the government, the public, and the market. The “top-down” government regulations form the main source of pressure for corporate green governance, manifested through punitive policies such as environmental regulations (Aragòn-Correa et al., 2020) and positive incentive policies like government subsidies and tax reductions (Wang & Wang 2023). At the same time, the “bottom-up” public power, driven by increasing attention to environmental issues and media coverage, has created an informal environmental supervision model (Wu et al., 2022), which has actively promoted corporate green governance. Additionally, key market participants in corporate green governance include financial institutions, green investors, and other enterprises (Flammer 2021; Feng & Yuan 2024). Some studies have focused on green supply chains (Li & Huang 2017), exploring the impact of supply chains on corporate behaviors such as environmental performance (Sinnandavar et al., 2018) and green innovation (Luo et al., 2024). Internal driving factors can be divided into two main categories: one is internal regulatory factors, including corporate governance structure, inputs, and effectiveness (Orazalin & Mahmood 2021; Sahoo and Kumar 2023; Liu et al., 2024), the other is internal sustainability factors such as technology-driven initiatives, operational efficiency, and financial performance (Wang et al., 2024; Yan et al., 2023; Liu et al., 2022).

Research on the evaluation of green governance has mainly focused on industry (Shah et al., 2022) or regional performance (Liu et al., 2022), with little attention paid to direct evaluations at the enterprise level. Early research on corporate green governance evaluation can be traced back to assessments of environmental performance, which were mainly approached in two ways: one uses single indicators to evaluate environmental performance, such as the increase in green innovation (Huang et al., 2016) or carbon dioxide emissions (Albitar et al., 2023). The other employs macro standards set by international organizations or governments, such as the ISO14031 standard, environmental performance evaluation standards (Dumay et al., 2010), and ESG criteria implemented by enterprises or third-party institutions, which assess performance based on three components: Environment, Social Responsibility, and Corporate Governance (Luo et al., 2024). As societal attention on corporate environmental performance has increased, research on the evaluation of corporate green governance has gradually emerged. While the selection of evaluation indicators still centers on environmental performance, more studies are beginning to incorporate governance factors, such as information-sharing cooperation capabilities (Barnes et al., 2016), the effectiveness of environmental regulations (Yuan et al., 2018), the green governance structure, mechanisms, effectiveness, and responsibilities (Li et al., 2019), and green monitoring (Huang et al., 2023). Evaluation methods have progressively employed Multi-Attribute Decision-Making (MADM) approaches, such as the entropy-weight TOPSIS method (Dos Santos et al., 2019), AHP (Meng & Shaikh 2023), DEA models (Matsumoto et al., 2020) and their derived models (Chen et al., 2021).

Based on the existing literature combining, several potential research gaps remain: (1) While existing literature has systematically linked the concepts of "green" and "governance", it is generally agreed that enterprises are key players in green governance, but a unified definition of corporate green governance has yet to be established. (2) Most existing studies focus on the internal and external factors influencing corporate green governance, but there has been insufficient attention to the external supply chain factors. Specifically, the direct link between the supply chain and corporate green governance has been underexplored, and the role of enterprises in driving green governance within the supply chain has not been adequately addressed. (3) There is a relative lack of quantitative assessment and measurement of CGGC. Current evaluation methods often overlook the inevitable uncertainty and fuzziness in decision-making processes, with many studies relying on a single evaluation strategy to derive final results. Moreover, comprehensive evaluations of corporate green governance are still limited, as most research focuses on the green governance level of enterprises in specific years, with few studies adopting a longitudinal perspective to examine trends in green governance over time.

3. Conceptual framework

3.1 Problem description for CGGC evaluation in the context of supply chain

In the context of supply chain globalization, corporate green governance has evolved from being solely a matter of individual enterprise actions to a systematic process spanning across supply chain segments and involving a wide range of stakeholders. CGGC is defined as the comprehensive ability to achieve sustainable development by optimizing internal resources horizontally within the company and coordinating vertically across the supply chain. This capability is characterized by three key features: governance entity, governance environment, and governance lifecycle. Specifically, governance entities refer to the enterprise as the central actor and responsible party in green governance, which standardizes green practices by integrating internal resources. The governance environment reflects how CGGC is influenced by green supply from upstream suppliers and green demand from downstream customers. In a complex supply chain environment, enterprises play a critical leadership role through demonstration, spillover, and forcing. The governance lifecycle illustrates how CGGC contributes to long-term value creation, with enterprises leveraging innovations in technology and business models to facilitate stakeholder engagement in sustainable development rather than limiting economic performance solely based on ecological capacity constraints.

Building upon these characteristics, the evaluation of CGGC from the supply chain perspective requires a multidimensional approach. This paper identifies three dimensions for measuring CGGC: green governance normative capability, green governance leadership capability, and green governance sustainable capability. Green governance normative capability reflects the internal structuring of governance practices. Green governance leadership capability highlights the corporate role in influencing green governance within the broader supply chain environment. Green governance sustainable capability focuses on the long-term viability of governance actions aimed at sustainable development. Accordingly, the evaluation of CGGC is framed as a MADM problem, as shown in Eq. (1), where the evaluation subject is the enterprise $X_i(i=1,2,\cdots,m)$, the attributes are the green governance capability indicators $c_j(j=1,2,\cdots,n)$, and the value of each attribute is denoted as x_{ij}.

$$H=\left(x_{ij}\right)_{m\times n}=\begin{array}{c} \\ X_1 \\ X_2 \\ \vdots \\ X_m \end{array}\begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \end{array} \tag{1}$$

For the MADM above, the evaluation process mainly consists of:

(1) Determine the evaluation proposal. The evaluation subject of this paper is the enterprise.
(2) Determine the attribute indicators. This paper needs to construct the evaluation framework of CGGC that incorporates the supply chain perspective.
(3) Calculate the weight of each attribute indicator. In this paper, taking into account the complexity and uncertainty of the evaluation of CGGC, the weights of the attribute indicators are obtained by integrating the cognitive degree of multiple experts on the attribute indicators.
(4) Calculate the comprehensive evaluation value. A scientific and reasonable evaluation method is chosen to calculate the comprehensive evaluation value of each proposal so as to obtain the comprehensive performance of the CGGC.

3.2 Evaluation framework of CGGC from the supply chain perspective

The evaluation framework of CGGC is constructed with the three dimensions of green governance normative, leadership, and sustainable capabilities, as shown in Table 1.

(1) Green governance normative capability C_1

Green governance normative capability reflects the ability of enterprises to regulate green governance behaviors through horizontal integration of internal resources. Three secondary dimensions—governance structure, governance input, and governance effectiveness—are used to assess the green governance normative capability. The governance structure is considered from green goal clarity C_{11} and green training C_{12} since proper top-level governance design and internal organizational collaboration can effectively guide the direction of corporate green development while also enhancing the green beliefs and consistency of action of employees (Abbas & Khan, 2023). Governance input is measured in terms of green investment C_{13} and green innovation C_{14} since they are the means of preventive inputs beforehand and response afterward in the face of environmental problems (Wang & Wang, 2023; Kong et al., 2016). Governance effectiveness is considered from green policy responsiveness C_{15} and green responsibility fulfillment C_{16}, respectively. The key indicator of corporate willingness to green governance is the ability to instantly take response actions such as environmental protection special projects and environmental emergencies in the face of relevant green policies enacted by the state, region, or industry (Sun et al., 2024). Green responsibility fulfillment, in particular, shows the extent of environmental protection and corporate social responsibility. This not only gives investors encouraging signals of corporate green governance, but it also objectively shows governance effectiveness, which can be reflected in the formulation of green governance decisions.

(2) Green governance leadership capability C_2

Green governance leadership capability reflects the ability of enterprises to lead green governance behaviors through demonstration, spillover, and forcing in the complex supply chain environment. This dimension reflects that corporate green governance behaviors are usually influenced by other enterprises in the supply chain or the external environment (Adhikari & Agrawal 2018). Three secondary dimensions—demonstration, spillover, and forcing—are used to assess the green governance leadership capability. The demonstration effect describes how an enterprise can serve as a green governance pioneer in the industry, offering other enterprises examples and guidance (Leary & Roberts, 2014). This is based on Environmental Management System (EMS) adoption C_{21} and ESG rating C_{22}. The spillover effect refers to the movement of information, technology, and personnel from one enterprise to another through supply chain relationships (Guo et al., 2024). This is measured in terms of employee exchange depth C_{23} as well as enterprise exchange degree C_{24}. Since there are no public statistics for some indicators in the framework, this paper refers to Matray (2021) and does the following: the natural

logarithm of the number of talents with postgraduate education and above is used to replace the employee exchange, and the natural logarithm of the number of patents filed by enterprises that have been cited by other organizations is used to replace the enterprise exchange. The forcing effect describes how an enterprise uses green governance to increase value creation, enhance quality and efficiency, and gradually impose barriers on other enterprises, forcing them to adopt green governance (Huang et al., 2021). This is measured by the number of green investors C_{25} and green bonds issuance C_{26}.

(3) Green governance sustainable capability C_3

Green governance sustainable capability is a reflection of corporate ability to implement green governance behaviors over a long period of time. Three secondary dimensions—drive, operation, and efficiency enhancement—are used to assess the green governance sustainable capability. Drive is the process of continuously empowering and accelerating corporate green governance through new technology, which are evaluated in terms of product R&D potential C_{31}, and digital transformation capacity C_{32}. Operation refers to the methods of ensuring ongoing corporate green governance through the subjective initiative of management (Shah et al., 2021), which is measured by executive green consciousness C_{33} and corporate internal control C_{34}. Efficiency enhancement gauges corporate stability and profitability, which serve as the foundation for the corporate ongoing investment in green governance (Sadiq et al., 2022). This is measured by enterprise growth C_{35} and return on investment (ROI) C_{36}.

Table 1
Evaluation framework of CGGC from the supply chain perspective

Dimension	Secondary Dimension	Indicator	Indicator description	Reference
Green governance normative capability C_1	Governance structure	Green goal clarity C_{11}	The degree of green development inclination of the enterprise itself can provide a guarantee for green governance from the top-level design level.	Li *et al.*, 2019
		Green training C_{12}	The company's green assessment or environmental education work, 0 for not carried out, 1 for carried out. This behavior can create an environment for employees to take green responsibility.	Huang *et al.*, 2023
	Governance input	Green investment C_{13}	The investment intensity of enterprises in green environmental protection projects is a long-term means of environmental governance and an immediate environmental protection decision.	Wang and Wang, 3
		Green innovation C_{14}	Innovation aimed at environmental protection, that is, enterprises achieve a balance between ecological protection and economic development through innovative research and development of green products, technologies, or processes.	Kong *et al.*, 2016
	Governance effectiveness	Green policy responsiveness C_{15}	The responsiveness of enterprises to green policies issued by the country, region, or industry, that is, whether they can take immediate response actions such as environmental protection special projects and environmental emergencies.	Sun *et al.*, 2024
		Green responsibility fulfillment C_{16}	The extent to which enterprises fulfill their social responsibilities in environmental protection.	Liu *et al.*, 2024
Green governance leadership capability C_2	Demonstration	EMS adoption C_{21}	Whether the company has adopted an environmental management system, with 0 for not adopted and 1 for adopted. This system comprehensively manages environmental factors to formulate green environmental policies.	Florida & Davison, 2001
		ESG rating C_{22}	The comprehensive performance of the company in the three dimensions of environment, society, and governance.	Luo *et al.*, 2024
	Spillover	Employee exchange depth C_{23}	Knowledge spillovers from mutual learning of green behaviors among employees of different enterprises.	Matray, 2021
		Enterprise exchange degree C_{24}	Knowledge spillovers from mutual learning of green behaviors among enterprises.	Jaffe *et al.*, 2000
	Forcing	Green investors C_{25}	The number of green investors in a company. Green investors tend to invest in green projects and are the supervisors and owners of the company.	Jiang *et al.*, 2021
		Green bond issuance C_{26}	Number of green bonds issued by companies as of the year, which are intended to raise funds for green projects.	Wang and Wang, 2001
Green governance sustainable capability C_3	Drive	Product R&D potential C_{31}	The growth rate of the proportion of enterprise R&D expenses to total operating income, that is, the importance that enterprises attach to R&D innovation that can be used for green governance in the future.	Sadiq *et al.*, 2022
		Digital transformation capacity C_{32}	The growth rate of the enterprise's digitalization level compared with the previous year, that is, the ability of enterprises to embed emerging means into green governance.	Liu *et al.*, 2023
	Operation	Executive green consciousness C_{33}	Corporate executives' concepts and understanding of future green governance.	Shah *et al.*, 2021
		Corporate internal control C_{34}	Enterprises' control over unknown risks in the process of green governance.	Oradi *et al.*, 2020
	Efficiency enhancement	Enterprise growth C_{35}	The stability of an enterprise's operating conditions is a necessary condition and economic foundation for the company to continue to carry out green governance in the future.	Liu *et al.*, 2022
		ROI C_{36}	The return on capital investment of an enterprise is the capital reserve and surplus resources for further green governance investment.	Sun, 2019

4. Research methods

4.1 Weights determination based on improved FBWM

For MADM (1), the set of evaluation indicators $\{c_1, c_2, \cdots, c_n\}$ is obtained from 3.2， and then the weights of the indicators need to be determined. FBWM is the latest MADM method that fully considers the uncertainty and ambiguity of experts in the decision-making process (Guo and Zhao 2017). In the process of determining the weights of CGGC indicators, it is necessary to consider the environmental dynamics of China's corporate green governance in the iterative development, the experts' familiarity with the evaluation subject and the degree of knowledge reserve, thus presenting a certain degree of decision-making ambiguity. Therefore, the paper establishes the group-based improved FBWM method to determine the indicator weights. The specific steps are as follows:

Step 1.1: Determine the best (most important) indicator and the worst (least important) indicator.

Based on the built evaluation framework, the best indicator c_B and the worst indicator c_W should be identified by experts.

Step 1.2: Define the importance level for fuzzy comparison.

Based on the nine levels of linguistic evaluation (Gumus 2009), a two-by-two comparison of the importance of each indicator is made. Then the linguistic importance variables are converted into triangular fuzzy numbers, as shown in Table 2.

Table 2
Linguistic variables

Importance	Triangular Fuzzy Numbers
Equal	(1,1,1)
Weak advantage	(1,2,3)
Not bad	(2,3,4)
Preferable	(3,4,5)
Good	(4,5,6)
Fairly good	(5,6,7)
Very good	(6,7,8)
Absolute	(7,8,9)
Perfect	(8,9,10)

Step 1.3: Get the fuzzy evaluation information vector of each expert.

Compare the best indicator c_B with other indicators, and get the fuzzy optimal comparison vector $\tilde{F}_B^k = \left(\tilde{f}_{B1}^k, \tilde{f}_{B2}^k, \cdots, \tilde{f}_{Bn}^k\right)$ of expert k, where $\tilde{f}_{Bj}^k$ is the importance level of the best indicator c_B relative to the indicators $c_j (j = 1,2,\cdots,n)$. It can be known that $\tilde{f}_{BB}^k = (1,1,1)$.

Compare other indicators with the worst indicator c_W, and get the fuzzy optimal comparison vector $\tilde{F}_W^k = \left(\tilde{f}_{1W}^k, \tilde{f}_{2W}^k, \cdots, \tilde{f}_{nW}^k\right)$ of expert k, where $\tilde{f}_{jW}^k$ is the importance level of the indicators $c_j (j = 1,2,\cdots,n)$ relative to the worst indicator c_W. It can be known that $\tilde{f}_{WW}^k = (1,1,1)$.

Step 1.4: Calculate the expert authority.

The formula (2) for calculating expert authority is as follows:

$$\theta^k = \frac{\theta_{1k} + \theta_{2k}}{\sum_{k=1}^{l} (\theta_{1k} + \theta_{2k})} \tag{2}$$

where θ_{1k} and θ_{2k} indicate the judgement basis and familiarity degree of the expert k. The judgment basis is divided into theoretical analysis, practical experience, domestic and foreign knowledge, and intuition; the corresponding scores are 0.3, 0.3, 0.3, 0.1, and its cumulative value of the option is θ_{1k}. The familiarity degree is divided into very familiar, familiar, a little familiar, general, not too familiar, and unfamiliar; the corresponding scores are 1, 0.8, 0.6, 0.4, 0.2, 0, and its cumulative value of the option is θ_{2k}.

Step 1.5: Get the aggregated evaluation information vector.
Use the following algorithm to aggregate the evaluation information matrices of *l* experts, and calculate the aggregated

evaluation information vector. The aggregation algorithm (3) is as follows:

$$\begin{aligned}\tilde{F}_B &= SWA_B(\tilde{F}_B^1, \tilde{F}_B^2, \cdots \tilde{F}_B^l) = \overset{l}{\underset{k=1}{\oplus}}\left(\theta^k \tilde{F}_B^k\right),\\ \tilde{F}_W &= SWA_W(\tilde{F}_W^1, \tilde{F}_W^2, \cdots \tilde{F}_W^l) = \overset{l}{\underset{k=1}{\oplus}}\left(\theta^k \tilde{F}_W^k\right),\end{aligned} \tag{3}$$

Step 1.6: Solve for indicator weights and check consistency.

Define the set of indicator weights as $\left\{\tilde{w}_1^*, \tilde{w}_2^*, \cdots, \tilde{w}_n^*\right\}$.. Then determine a solution that the maximum absolute gaps $\left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{f}_{Bj}\right|$ and $\left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{f}_{jW}\right|$ for all j are minimized, where $\tilde{w}_B$ denotes the weight of the best indicator c_B and $\tilde{w}_W$ denotes the weight of the worst indicator c_W. The constrained optimization problem is constructed as shown in Eq. (4):

$$\begin{aligned}&\min \max_j \left\{\left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{f}_{Bj}\right|, \left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{f}_{jW}\right|\right\}\\ &s.t.\begin{cases}\sum_{j=1}^{n} R(\tilde{w}_j) = 1\\ l_j^w \le m_j^w \le u_j^w\\ l_j^w \ge 0\\ \forall j \in N_+\end{cases}\end{aligned} \tag{4}$$

where $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$, $l_j^w \le m_j^w \le u_j^w$, $R(\tilde{w}_j) = \frac{l_j + 4m_j + u_j}{6}$. Eq. (4) can be transferred to nonlinearly constrained optimization problem (5) as follows:

$$\begin{aligned}&\min \tilde{\xi}\\ &s.t.\begin{cases}\left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{f}_{Bj}\right| \le \tilde{\xi}\\ \left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{f}_{jW}\right| \le \tilde{\xi}\\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1\\ l_j^w \le m_j^w \le u_j^w\\ l_j^w \ge 0\\ \forall j \in N_+\end{cases}\end{aligned} \tag{5}$$

where $\tilde{\xi} = (l^{\xi}, m^{\xi}, u^{\xi})$, $l^{\xi} \le m^{\xi} \le u^{\xi}$. Assume that the optimal objective value is $\xi^* = (k^*, k^*, k^*)$, $k^* \le l^{\xi}$, and Eq. (5) can be transferred to Eq. (6):

$$\begin{aligned}&\min \tilde{\xi}^*\\ &s.t.\begin{cases}\left|\frac{(l_B^w, m_B^w, u_B^w)}{(l_j^w, m_j^w, u_j^w)} - (l_{Bj}, m_{Bj}, u_{Bj})\right| \le (k^*, k^*, k^*)\\ \left|\frac{(l_j^w, m_j^w, u_j^w)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW})\right| \le (k^*, k^*, k^*)\\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1\\ l_j^w \le m_j^w \le u_j^w\\ l_j^w \ge 0\\ \forall j \in N_+\end{cases}\end{aligned} \tag{6}$$

By solving Eq. (6), the fuzzy weights can be obtained, and then use $R(\tilde{w}_j)=\frac{l_j+4m_j+u_j}{6}$ to defuzzify. Consistency Ratio (CR) is used for testing. The value of $CR=\frac{\xi^*}{CI}$ which is less than 0.1 means that it passes the consistency test, and the closer it is to 0, the more reliable the results are.

4.2 Evaluation value calculation based on CoCoSo

When tackling real-world problems, different experts may hold distinct framework and viewpoints, resulting in diverse solutions. Traditional decision-making methods (e.g., VIKOR, WASPAS, TOPSIS, etc.) all use only one evaluation strategy in calculating the final decision value, which lacks reliability to some extent. CoCoSo is an improved decision-making method that combines three different comparable evaluation strategies to arrive at the final decision value (Yazdani et al. 2019). However, the traditional CoCoSo method still has some drawbacks. On the one hand, the second evaluation strategy influences the final ranking far more than the other two, and on the other hand, it ignores the normalization of the three strategies together. Therefore, in order to increase the reasonableness of the decision-making results, this paper integrates the numerical and ordinal values of the three strategies to improve the final ranking function of the traditional CoCoSo technique. The specific steps are as follows:

Step 2.1: Determine the standardized evaluation matrix.

Using Eq. (7), convert MADM (1) into a standardized assessment matrix:

$$b_{ij}=\begin{cases}\dfrac{x_{ij}-\min\limits_i x_{ij}}{\max\limits_i x_{ij}-\min\limits_i x_{ij}}, \text{ benefit indicator}\\ \dfrac{\max\limits_i x_{ij}-x_{ij}}{\max\limits_i x_{ij}-\min\limits_i x_{ij}}, \text{ cost indicator}\end{cases} \tag{7}$$

Step 2.2: Compute the sum of the weighted comparability sequence S_i and power-weighted comparability sequence P_i by Eqs. (8-9).

$$S_i=\sum_{j=1}^{n} w_j b_{ij} \tag{8}$$

$$P_i=\sum_{j=1}^{n}\left(b_{ij}\right)^{w_j} \tag{9}$$

where w_j is determined by FBWM; $\sum\limits_{j=1}^{n} w_j=1$, $w_j\geq 0$.

Step 2.3: Calculate the relative importance.

Calculate the arithmetic mean strategy M_i^1 (Comprehensive Evaluation Strategy I), the relative scoring strategy M_i^2 (Comprehensive Evaluation Strategy II), and the balanced compromise strategy M_i^3 (Comprehensive Evaluation Strategy III) by Eqs. (10-12).

$$M_i^1=\frac{S_i+P_i}{\sum\limits_{i=1}^{m}\left(S_i+P_i\right)}, \tag{10}$$

$$M_i^2=\frac{S_i}{\min\limits_i S_i}+\frac{P_i}{\min\limits_i P_i}, \tag{11}$$

$$M_i^3=\frac{\alpha S_i+(1-\alpha)P_i}{\alpha\max\limits_i S_i+(1-\alpha)\max\limits_i P_i}, \alpha\in[0,1]. \tag{12}$$

Step 2.4: Calculate comprehensive evaluation value M_i.

According to the research of Kumar and Kumar (2024), the outcomes of the decision-making model are more logical when numerical and ordinal values are taken into account simultaneously while determining the comprehensive evaluation value M_i based on the three evaluation strategies mentioned above, as shown in Eq. (13):

$$M_i = \sum_{\rho=1}^{3} \sqrt{\frac{1}{2}\left((\frac{M_i^{\rho}}{\max\limits_i M_i^{\rho}})^2 + \left(1 - \frac{r_i^{\rho}}{m}\right)^2 \right)}, i = 1,2,\ldots,m \tag{13}$$

where r_i^{ρ} denotes the ranking of ρ evaluation strategy value for an evaluated enterprise $X_i (i = 1,2\cdots,m)$; $\rho = 1,2,3$.

4.3 Sample, data and flowchart

In the evaluation of CGGC, the improved FBWM is utilized to determine the weights of indicators, which requires experts' input on the evaluation framework for CGGC. Subsequently, the CoCoSo is applied to calculate the comprehensive evaluation value, which necessitates the collection of specific values for each indicator under the framework of CGGC.

(1) To give judging information on the CGGC evaluation framework, 15 professionals with knowledge of green governance research or experience advancing green growth in the industrial sector were chosen. The number of experts was determined based on group decision-making guidelines (Robbins 1994) and the sample size recommendations for parameter estimation (Anderson et al., 2017).

(2) The paper focuses on core enterprises in the YRD for two reasons: First, there has been outstanding leadership in the YRD, which represents notable regional accomplishments in green government. Second, core enterprises, as leaders of their respective industries and key players in industrial structure (Jacobides et al., 2016). They can use the "green bullwhip effect" to support not only their own green transformations but also the cooperative green governance initiatives of other enterprises (Braguinsky et al., 2023). To define these core enterprises, this study adopts the method proposed by Jannati et al. (2020), which identifies the top 25% of enterprises by total assets in the YRD as core enterprises. Considering data availability, the initial sample consists of 1,153 A-share listed enterprises in the YRD from 2014 to 2022. The sample was then refined using the following framework: exclusion of ST or ST* listed companies during the sample period; exclusion of financial enterprises; exclusion of enterprises with a debt-to-asset ratio exceeding 1; and exclusion of enterprises with missing relevant data. In total, 255 core enterprises in the YRD were selected as the evaluation subjects. Data for the CGGC indicators were sourced from China Financial Information Network, Choice, China Stock Market & Accounting Research Database (CSMAR), and National Intellectual Property Administration. The flowchart of the proposed evaluation framework is shown in Fig. 1.

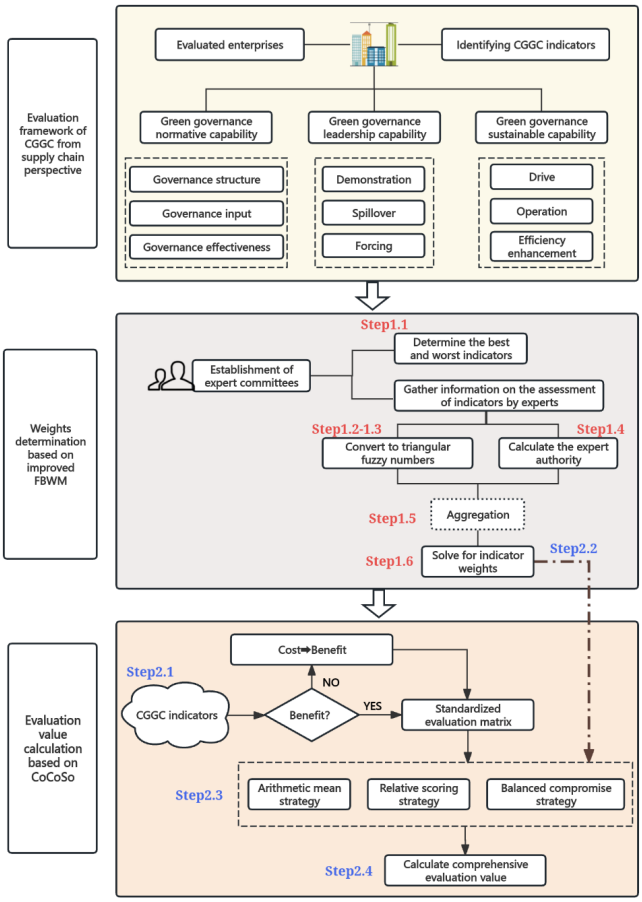

Fig. 1. Flowchart of the proposed evaluation framework

5. Results and discussion

5.1 Comprehensive evaluation of CGGC in YRD from the supply chain perspective

Calculate the indicator weights and comprehensive evaluation value of CGGC in the YRD using the evaluation model proposed in Section 3.3.

Step 1: In the following, the procedure of the improved FBWM approach is given to estimate the indicator weights.

Step 1.1: Determine the best (most important) indicator and the worst (least important) indicator. In the dimensions, the best and worst indicators are green governance normative capability C_1 and green governance leadership capability C_2. Within the dimension of C_1, the best and worst indicators are green goal clarity C_{11} and green training C_{12}. Within the dimension of C_2, the best and worst indicators are enterprise exchange degree C_{24} and green bond issuance C_{26}. Within the dimension of C_3, the best and worst indicators are enterprise growth C_{35} and ROI C_{36}.

Step **1.2-1.5**: Firstly, based on Table 2, triangular fuzzy numbers representing the relative importance of each indicator were derived from the evaluations provided by 15 experts. Subsequently, calculate the expert authority by Eq. (2), as shown in Table 3. Finally, obtain the aggregated expert evaluation information vectors by Eq. (3), as presented in Tables 4 and 5. The fuzzy relative importance for sub-dimensions is provided in Appendix A.

Table 3
Expert authority

No.	1	2	3	4	5	6	7	8
θ^k	0.060	0.089	0.071	0.083	0.071	0.089	0.030	0.054
No.	9	10	11	12	13	14	15	
θ^k	0.060	0.065	0.089	0.018	0.077	0.107	0.036	

Table 4
Fuzzy relative importance of dimensions (BO)

	C_1	C_2	C_3
Best indicator C_1	(1,1,1)	(5.435,6.435,7.435)	(2.804,3.804,4.804)

Table 5
Fuzzy relative importance of dimensions (OW)

	Worst indicator C_2
C_1	(5.435,6.435,7.435)
C_2	(1,1,1)
C_3	(2.524,3.524,4.524)

Step 1.6: According to Equations (4)-(6), the fuzzy weights of three dimensions of the CGGC are obtained and quantified into precise values. The weights of dimensions are respectively green governance normative capability (0.672), green governance leadership capability (0.092), and green governance sustainable capability (0.236). Similarly, the weights of the sub-dimensions are calculated, with the results presented in Table 6. The detailed calculation process is provided in the Appendix B.

Table 6
Weights of indicators for CGGC evaluation

Dimension	Fuzzy weight	Weight	Indicator	Fuzzy weight	Weight
C_1	(0.552,0.695,0.695)	0.672	C_{11}	(0.365,0.365,0.406)	0.372
			C_{12}	(0.041,0.041,0.048)	0.042
			C_{13}	(0.108,0.129,0.194)	0.136
			C_{14}	(0.136,0.172,0.269)	0.182
			C_{15}	(0.118,0.143,0.221)	0.152
			C_{16}	(0.094,0.111,0.159)	0.116
C_2	(0.083,0.094,0.094)	0.092	C_{21}	(0.123,0.165,0.194)	0.163
			C_{22}	(0.125,0.166,0.193)	0.164
			C_{23}	(0.109,0.152,0.181)	0.150
			C_{24}	(0.315,0.370,0.386)	0.363
			C_{25}	(0.079,0.121,0.152)	0.119
			C_{26}	(0.039,0.042,0.042)	0.041
C_3	(0.149,0.243,0.297)	0.236	C_{31}	(0.099,0.121,0.195)	0.130

C_{32}	(0.103,0.129,0.216)	0.139
C_{33}	(0.107,0.132,0.214)	0.142
C_{34}	(0.197,0.219,0.255)	0.221
C_{35}	(0.321,0.321,0.360)	0.328
C_{36}	(0.039,0.039,0.046)	0.040

Step 2: In the following, the procedure of the improved CoCoSo approach is given to evaluate the CGGC.

Step 2.1: All the indicators are benefit and the standardization matrix is determined by Eq. (7).

Step 2.2: Compute the sum of the weighted comparability sequence and power-weighted comparability sequence by Eqs. (8-9).

Step 2.3-2.4: Calculate M_i of 255 core YRD enterprises for the period of 2014-2022 by Eqs. (10-13). Subsequently, the evaluation values under the three dimensions of green governance normative capability, green governance leadership capability and green governance sustainable capability are calculated separately.

Due to the excessive amount of data involved in this section, it is not convenient to expand it in the main text, and it will be further analyzed in the form of graphs and charts in section 4.2.

5.2 Evaluation results analysis of CGGC in the YRD from the supply chain perspective

5.2.1 Overall analysis of CGGC

The descriptive statistics of the CGGC in the YRD are shown in Table 7. From 2014 to 2022, the mean value of the CGGC exhibited a fluctuating yet upward trajectory. Despite an average annual growth rate of 4.46%, actual values remained within the range of 1.44 to 2.04, indicating that the CGGC in the YRD remains in a nascent phase. Analyzing the median reveals that prior to 2019, most CGGC are below the overall mean. However, from 2019 onwards, the median surpassed the mean for the first time, signaling a gradual improvement in corporate governance. Notably, the COVID-19 pandemic, as an unforeseen "black swan" event, disrupted firms' operations and forced a shift in focus toward short-term survival and recovery (Chudziński *et al.*, 2023), which led to a significant decline in the median. Furthermore, extreme value analysis shows that the disparity between the highest and lowest values of green governance capability increased from 2.1 in 2014 to 2.19 in 2022, underscoring the growing divergence in governance levels across firms. In sum, while there has been progress, green governance in YRD enterprises remains underdeveloped, with considerable inter-enterprise and regional disparities that warrant further improvement.

Table 7
Descriptive statistics of CGGC in the YRD (2014-2022)

Year	Mean	Median	Min	Max	Standard deviation	Observation
2014	1.44	1.30	0.78	2.88	0.56	255
2015	1.47	1.36	0.56	2.93	0.57	255
2016	1.57	1.46	0.73	2.92	0.60	255
2017	1.63	1.60	0.77	2.97	0.58	255
2018	1.69	1.65	0.78	2.99	0.57	255
2019	1.76	1.79	0.78	2.98	0.59	255
2020	1.70	1.65	0.77	2.90	0.56	255
2021	1.94	2.00	0.79	2.98	0.58	255
2022	2.04	2.15	0.78	2.97	0.58	255

To explore the reasons behind this relatively low overall capability, the three dimensions of green governance—normative capability, leadership capability, and sustainable capability—were assessed, as illustrated in Fig. 2.

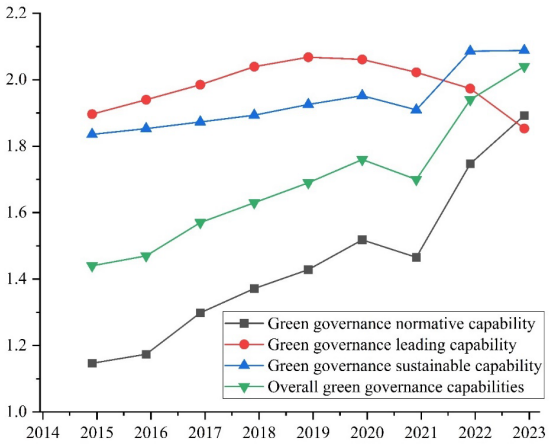

Fig. 2. Trends in the dimensions of CGGC in the YRD

Green governance leadership capability demonstrated a volatile trajectory, peaking initially before declining from 1.90 in 2014 to 1.85 in 2022, with a negative growth rate of -0.29%. Conversely, green governance normative capability (6.46%) and green governance sustainable capability (1.63%) fluctuate and increase. Notably, all three dimensions saw marked declines in 2020, primarily due to the pandemic's economic pressures, which forced firms to deprioritize long-term green governance objectives in favor of short-term survival strategies (Diesendorf, 2020). Following the initial crisis, heightened public awareness and governmental pressure led enterprises to refocus on sustainable development and environmental governance, fostering recovery in both normative and sustainable capabilities. However, leadership capability, particularly in the context of supply chain disruptions, remained slow to rebound (Um and Han, 2021). To address this, regional policies must focus on enhancing leadership within the supply chain, while continuously fostering improvements in normative and sustainable governance dimensions.

The YRD region has emerged as a leader in green governance, exhibiting strong regional synergies in policy design and execution (Feng *et al.*, 2024). However, due to the differences in environmental awareness, economic development level and innovation capability, CGGC across the region show significant unevenness. From the perspective of horizontal development trend, the overall fluctuating upward trend of CGGC in each jurisdiction between 2014 and 2022, with the average annual growth rates of Jiangsu Province (4.82%), Anhui Province (4.67%), Zhejiang Province (3.77%), and Shanghai Municipality (3.21%) in the order of the average annual growth rate, as shown in Fig. 3. From the perspective of vertical development differences, during the period from 2014 to 2022, the CGGC of the four regions are, in descending order, Shanghai, Anhui, Zhejiang, and Jiangsu, with the mean values of 1.79, 1.74, 1.69, and 1.56, respectively, and the mean value of the overall CGGC in the YRD is 1.69. This suggests that regional resource endowments and economic structures significantly influence CGGC, and future policies must align more closely with regional characteristics to improve overall CGGC.

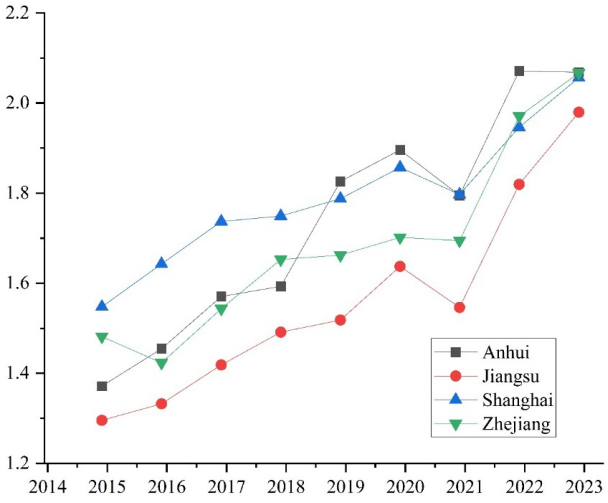

Fig. 3. Overall development trend of CGGC by region in the YRD

5.2.2 Heterogeneity analysis of CGGC

(1) Ownership heterogeneity

The trend of CGGC of YRD enterprises with different ownership natures is shown in Figure 4, and the ownership has an important impact on the enterprises' policy response and resource acquisition. The green governance capabilities of sate-owned enterprises (SOEs) grow from 1.50 in 2014 to 2.06 in 2022, with a growth rate of 37%, while the green governance capabilities of non-sate-owned enterprises (non-SOEs) grow from 1.39 to 2.03, with a growth rate of 46%. This indicates that the baseline level of green governance capabilities of non-SOEs is slightly lower than that of SOEs, but they are able to respond quickly in the face of environmental pressures and changes in market demand, with a significant upward trend. Taking the 2020 black swan event as a watershed, both SOEs and non-SOEs suffered a certain impact between 2014 and 2019, SOEs consistently maintained the dominant position of green governance, with an average annual growth rate of 3.46%, and their green governance capabilities were higher than the overall average of enterprises in the YRD. This is attributed to the ability of SOEs in resource allocation, policy orientation, and social responsibility greening, which makes them pay more attention to environmental and social benefits while pursuing economic benefits (Shi *et al.*, 2023). And after 2020, the performance of state-owned and non-SOEs converges, with average annual growth rates of 6.29% and 6.27%, respectively. This change suggests that while SOEs have been able to maintain stability with government support, non-SOEs have shown potential for rapid improvement during the crisis due to greater governance flexibility and market acumen.

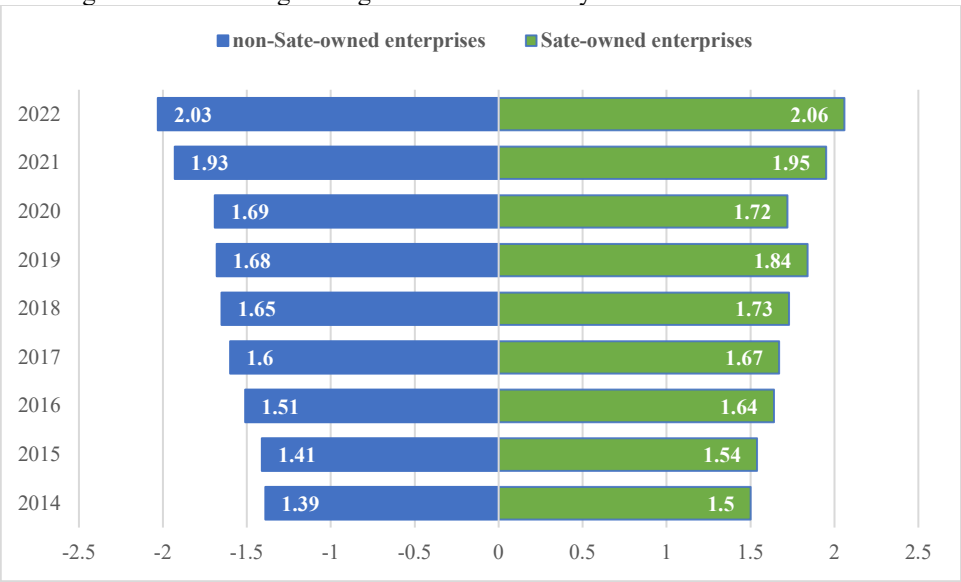

Fig. 4. CGGC in the YRD with different ownership natures

(2) Industry heterogeneity

Enterprises in the YRD are classified into heavily polluting enterprises (HPEs) and non-heavily polluting enterprises (non-HPEs) according to the *Catalogue for Classified Management of Environmental Protection Verification of Listed Companies (June 2008)* published by the Ministry of Ecological Protection. As depicted in Fig. 5, both categories demonstrate an upward trajectory in CGGC, with HPEs consistently exhibiting stronger capabilities. This suggests that industry characteristics determine the environmental regulatory pressure and technology adaptation path. Specifically, the green governance capabilities of HPEs grow from 1.70 in 2014 to 2.28 in 2022, with a growth rate of 34%, while those of non-HPEs grow from 1.36 to 1.97, with a growth rate of 46%. HPEs are mostly national pillar industries such as power, chemical and coal, which are subject to more stringent environmental regulations, thereby driving higher CGGC. However, the relatively lower environmental impact of non-HPEs, coupled with the reduced complexity and cost of green transformation, enables these enterprises to more effectively enhance their CGGC.

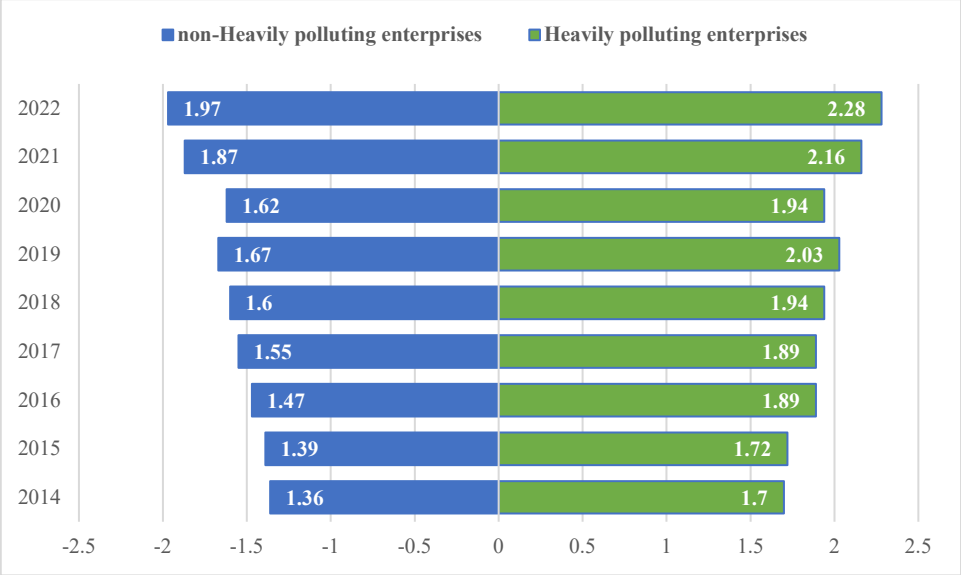

Fig. 5. Green governance capabilities of different polluting enterprises in the YRD

Furthermore, enterprises in the YRD are reclassified into labor-intensive enterprises (LIEs) and technology-intensive enterprises (TIEs), based on the relative contributions of labor and technology within their production processes. As shown in Fig. 6, both categories exhibit an upward trend in their CGGC, with TIEs consistently demonstrating superior performance. This trend is largely driven by increasingly stringent environmental regulations and the growing emphasis on sustainable development. TIEs, with their more advanced and efficient production technologies, are able to minimize resource wastage and energy consumption, thereby facilitating more efficient green production.

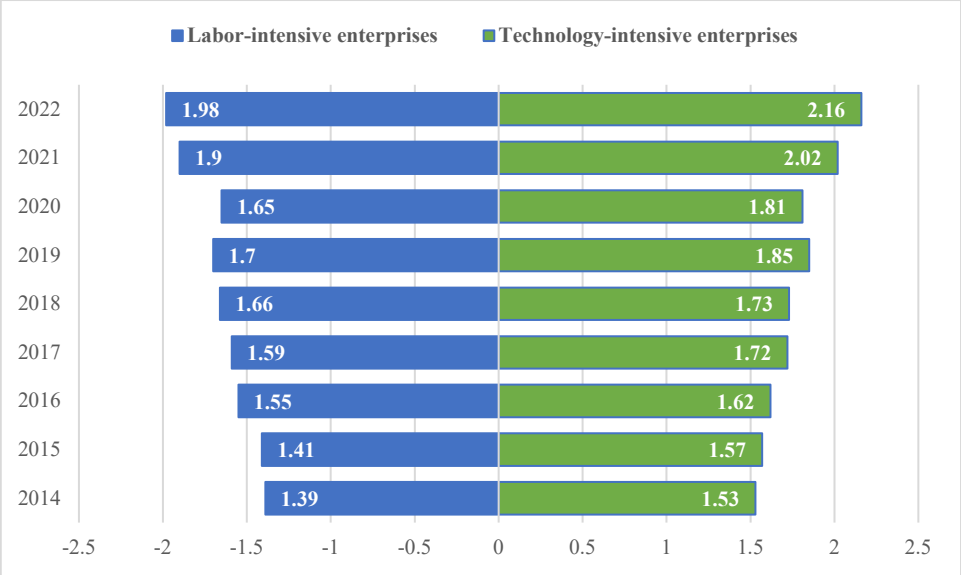

Fig. 6. Green governance capabilities of different intensive enterprises in the YRD

Nevertheless, the CGGC of LIEs grow from 1.39 in 2014 to 1.98 in 2022, with a growth rate of 41.90%, while those of TIEs increase from 1.53 to 2.16, with a growth rate of 41.54%. The similarity in growth rates highlights the increasing trend of cross-industry collaboration in the context of globalization and an increasingly integrated industrial chain. Through technology transfer and the exchange of best practices, LIEs gain access to cutting-edge green governance technologies, enabling them to transition to green production. Consequently, both LIEs and TIEs have experienced similar advancements in their CGGC, underscoring the pivotal role of cross-industry collaboration and policy incentives in driving the overall enhancement of CGGC.

(3) Lifecycle heterogeneity

The distinct characteristics of various lifecycle stages—such as enterprise size, growth dynamics, investment and financing strategies, and the propensity for research, development, and innovation—underscore the shifting needs and challenges in advancing CGGC throughout an enterprise's evolution. Leveraging Dickinson's (2011) cash flow modeling framework, the

lifecycle of an enterprise is categorized into four stages: start-up, growth, maturity, and decline, determined by the net cash flow combinations across operations, investments, and financing activities.

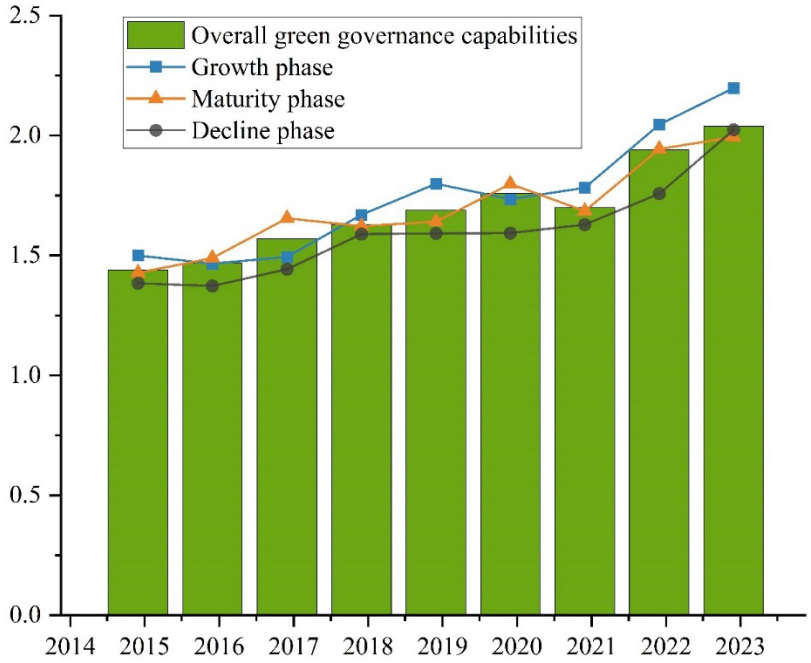

Fig. 7. CGGC of different lifecycle stages in the YRD

Due to the limitations inherent in the data sample, the core enterprises in the YRD are primarily concentrated in the growth, maturity, and decline stages. As depicted in Fig. 7, the CGGC across these stages exhibits a fluctuating upward trajectory: enterprises in the growth stage increased from 1.50 in 2014 to 2.20 in 2022, reflecting a 46.64% rise; those in the maturity phase grew from 1.43 to 1.99, a 39.56% increase; and enterprises in the decline phase rose from 1.38 to 2.02, marking a 46.19% improvement. Enterprises in the growth phase, experiencing rapid expansion, exhibit a marked increase in CGGC, predominantly driven by policy imperatives and heightened social responsibility expectations. Their agility in adapting to technological innovations and managerial shifts further accelerates the advancement of green governance. Mature enterprises, benefiting from higher profitability and stable cash flows, are positioned to undertake sustained green governance investments (Gao *et al.*, 2023). However, the rate of CGGC improvement in this stage is slower compared to that of growth-phase enterprises, constrained by the stabilization of growth. In contrast, declining enterprises, despite their limited growth potential, increasingly view green governance as a vital means of transformation under external pressures and policy incentives. Through the optimization of resource allocation, enhancement of energy efficiency, and implementation of emission-reduction initiatives, these enterprises actively pursue survival opportunities, achieving notable CGGC improvements at a rate between that of growth and mature enterprises (Mourdoukoutas & Stefanidis, 2023).

6. Implications

6.1 Theoretical implications

This study contributes to the theoretical understanding of CGGC by revealing its uneven development across regions, ownership types, industries, and enterprise life cycles.

First, the study extends existing literature by proposing a multidimensional evaluation framework from a supply chain perspective, integrating normative, leadership, and sustainable capabilities. This framework deepens insights into how enterprises coordinate internal resources, influence supply chain networks, and sustain long-term governance efforts. Second, the study contributes methodologically by introducing a refined evaluation model that combines the improved FBWM and CoCoSo methods, enhancing decision-making accuracy and accommodating uncertain or incomplete information. Third, by analyzing CGGC evolution in the Yangtze River Delta from 2014 to 2022, this study highlights inter-enterprise heterogeneity and dynamic governance patterns across ownership types, industries, and firm life cycles—offering a more comprehensive and temporal view of CGGC development.

6.2 Practical implications

This study offers several actionable insights for policymakers and business practitioners.

First, to address the uneven development of CGGC across the YRD, regional integration should be further promoted through

shared green governance practices, policy alignment, and optimized resource distribution, thereby narrowing regional and enterprise disparities. Especially, while maintaining green governance normative and sustainable capabilities, it is imperative to reinforce leadership capabilities in green governance by leveraging the pivotal role of core supply chain enterprises.

Second, given the disparities between SOEs and non-SOEs in resource acquisition and governance flexibility, differentiated policies should be designed to support each ownership structure. Non-SOEs should be incentivized with tax benefits and financing support to unlock their green governance potential, while SOEs should focus on enhancing their resource integration and social responsibility, thus solidifying their role as green governance exemplars.

Third, high-pollution industries should continue to strengthen environmental constraints and technical standards to maintain their green governance advantages. Non-high-pollution industries can be further incentivized through policy guidance and technical support, unlocking further potential for improvement. Moreover, fostering cross-industry collaboration between labor-intensive and technology-intensive sectors through technology transfer and knowledge sharing will enhance overall CGGC.

Fourth, tailored incentive policies should be devised for enterprises at different lifecycle stages. Growth-phase enterprises should receive subsidies for technological innovation and market access to expedite their green transformation, while mature enterprises should be encouraged to engage in long-term investments and R&D. For declining-phase enterprises, support for resource optimization and green restructuring will facilitate overcoming challenges and achieving recovery.

7. Limitations and prospects

While this paper offers an initial analysis of CGGC development trends and future trajectories, certain limitations remain that warrant further exploration. First, the concept of green governance evolves as practices advance, and current data collection is limited in scope and depth. Future research should broaden its scope to enhance the generalizability of the findings. Second, the reliance on expert surveys for determining indicator weights, while valuable, could be augmented by incorporating big data analytics or machine learning techniques to increase objectivity and scientific robustness. Lastly, future research should systematically explore the factors influencing CGGC and their configurational effects from the supply chain perspective, offering both theoretical insights and practical guidance for optimizing green governance strategies.

8. Conclusions

This paper systematically evaluates CGGC in the YRD from 2014 to 2022. Initially, a comprehensive evaluation framework for CGGC was established, incorporating the supply chain perspective. Subsequently, the improved FBWM and CoCoSo methods were employed to calculate the comprehensive evaluation value of CGGC, accounting for decision-making uncertainties. Finally, the development trends and potential of CGGC in the YRD were examined from both a general perspective and through the lens of enterprise heterogeneity, considering ownership structure, industry characteristics, and lifecycle stages. The key findings are as follows:

(1) CGGC in the YRD has demonstrated a fluctuating upward trajectory; however, the overall level remains relatively low, with pronounced regional and inter-enterprise disparities. In terms of dimensional performance, green governance normative and sustainable capabilities have consistently advanced, driven by external pressures and internal demands, while leadership capability in green governance has been significantly disrupted by external shocks, with a slow recovery.

(2) SOEs exhibit a dominant position in green governance, with consistently higher CGGC scores compared to non-SOEs. Nonetheless, non-SOEs are gradually unveiling substantial growth potential, particularly in the post-pandemic era, where the green governance performance of both ownership natures is converging.

(3) CGGC exhibits significant heterogeneity across industries. Specifically, HPEs and TIEs exhibit superior CGGC, whereas non-HPEs and LIEs show faster improvements in their CGGC, reflecting a pronounced late-mover advantage.

(4) The rate of CGGC improvement varies according to the enterprise lifecycle stage. Growth-phase enterprises exhibit the most rapid improvement, followed by declining-phase enterprises, with mature-phase enterprises demonstrating the slowest progression.

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Appendix

Appendix A: Fuzzy relative importance for sub-dimensions

Table A-1
Fuzzy relative importance of the normative sub-dimension (BO)

	Best indicator C_{11}
C_{11}	(1,1,1)
C_{12}	(6.744,7.744,8.744)
C_{13}	(3.077,4.018,4.958)
C_{14}	(2.470,3.321,4.173)
C_{15}	(2.845,3.744,4.643)
C_{16}	(3.488,4.488,5.488)

Table A-2
Fuzzy relative importance of the normative sub-dimension (OW)

	Worst indicator C_{12}
C_{11}	(6.744,7.744,8.744)
C_{12}	(1,1,1)
C_{13}	(3.435,4.357,5.280)
C_{14}	(3.542,4.464,5.387)
C_{15}	(3.440,4.363,5.286)
C_{16}	(2.899,3.792,4.685)

Table A-3
Fuzzy relative importance of the leadership sub-dimension (BO)

	Best Indicator C_{24}
C_{21}	(2.661,3.524,4.387)
C_{22}	(2.548,3.470,4.393)
C_{23}	(2.333,3.077,3.821)
C_{24}	(1,1,1)
C_{25}	(3.381,4.381,5.381)
C_{26}	(6.560,7.560,8.560)

Table A-4
Fuzzy relative importance of the leadership sub-dimension (OW)

	Worst Indicator C_{26}
C_{21}	(4.256,5.256,6.256)
C_{22}	(4.310,5.280,6.250)
C_{23}	(3.923,4.923,5.923)
C_{24}	(6.560,7.560,8.560)
C_{25}	(3.202,4.202,5.202)
C_{26}	(1,1,1)

Table A-5
Fuzzy relative importance of the sustainable sub-dimension (BO)

	Best Indicator C_{35}
C_{31}	(2.845,3.845,4.845)
C_{32}	(2.685,3.685,4.685)
C_{33}	(2.702,3.631,4.560)
C_{34}	(1.369,2.196,3.024)
C_{35}	(1,1,1)
C_{36}	(6.083,7.083,8.083)

Table A-6
Fuzzy relative importance of the sustainable sub-dimension (OW)

	Worst Indicator C_{36}
C_{31}	(3.333,4.333,5.333)
C_{32}	(3.548,4.518,5.488)
C_{33}	(2.958,3.851,4.744)
C_{34}	(3.524,4.446,5.369)
C_{35}	(6.083,7.083,8.083)
C_{36}	(1,1,1)

Appendix B: Indicator weights calculation

(1) Dimension indicator weights

Equation (B-1) for fuzzy relative importance of dimensions can be calculated based on Equation (6), using the parameters provided in Tables 4 and 5.

$$
\begin{aligned}
&\min \tilde{\xi}^{*} \\
&s.t.\begin{cases}
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_1^w,m_1^w,u_1^w)}-(l_{11},m_{11},u_{11})\right|\le(k^*,k^*,k^*) \\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{12},m_{12},u_{12})\right|\le(k^*,k^*,k^*) \\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_3^w,m_3^w,u_3^w)}-(l_{13},m_{13},u_{13})\right|\le(k^*,k^*,k^*) \\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{12},m_{12},u_{12})\right|\le(k^*,k^*,k^*) \\
\left|\dfrac{(l_2^w,m_2^w,u_2^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{22},m_{22},u_{22})\right|\le(k^*,k^*,k^*) \\
\left|\dfrac{(l_3^w,m_3^w,u_3^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{32},m_{32},u_{32})\right|\le(k^*,k^*,k^*) \\
\sum_{j=1}^{3}R(\tilde{w}_j)=1 \\
l_j^w\le m_j^w\le u_j^w \\
l_j^w\ge 0 \\
\forall j\in N_+
\end{cases}
\end{aligned}
\tag{B-1}
$$

Then, we can obtain the following nonlinearly constrained optimization problem (B-2) represented by concrete numbers.

$$\min k^*$$

$$s.t.\begin{cases} l_1 - 5.435*u_2 \le k^* u_2; l_1 - 5.435*u_2 \ge -k^* u_2; \\ m_1 - 6.435*m_2 \le k^* m_2; m_1 - 5.435*m_2 \ge -k^* m_2; \\ u_1 - 7.435*l_2 \le k^* l_2; u_1 - 7.435*l_2 \ge -k^* l_2; \\ l_1 - 2.804*u_3 \le k^* u_3; l_1 - 2.804*u_3 \ge -k^* u_3; \\ m_1 - 3.804*m_3 \le k^* m_3; m_1 - 3.804*m_3 \ge -k^* m_3; \\ u_1 - 4.804*l_3 \le k^* l_3; u_1 - 4.804*l_3 \ge -k^* l_3; \\ l_3 - 2.524*u_2 \le k^* u_2; l_3 - 2.524*u_2 \ge -k^* u_2; \\ m_3 - 3.524*m_2 \le k^* m_2; m_3 - 3.524*m_2 \ge -k^* m_2; \\ u_3 - 4.524*l_2 \le k^* l_2; u_1 - 4.524*l_2 \ge -k^* l_2; \\ l_1 + 4*m_1 + u_1 + l_2 + 4*m_2 + u_2 + l_3 + 4*m_3 + u_3 = 6; \\ l_1 \le m_1 \le u_1; l_2 \le m_2 \le u_2; l_3 \le m_3 \le u_3; \\ l_1 \ge 0; l_2 \ge 0; l_3 \ge 0; \\ k \ge 0 \end{cases} \tag{B-2}$$

By solving Eq. (B-2), the optimal fuzzy weights of three indicators (C_1 'green governance normative capability'; C_2 'green governance leadership capability'; C_3 'green governance sustainable capability') can be calculated, which are

$\widetilde{w}_1^* = (0.552, 0.695, 0.695)$; $\widetilde{w}_2^* = (0.083, 0.094, 0.094)$;

$\widetilde{w}_3^* = (0.149, 0.243, 0.297)$; $\tilde{\xi}^* = (0.944, 0.944, 0.944)$

(2) Indicator weights of normative sub-dimension

Eq. (B-3) for the fuzzy relative importance of the normative sub-dimension can be calculated based on Eq. (6) using the parameters provided in Tables A-2 and A-3.

$$
\begin{aligned}
&\min \tilde{\xi}^* \\
&s.t.\begin{cases}
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_1^w,m_1^w,u_1^w)}-(l_{11},m_{11},u_{11})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{12},m_{12},u_{12})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_3^w,m_3^w,u_3^w)}-(l_{13},m_{13},u_{13})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_4^w,m_4^w,u_4^w)}-(l_{14},m_{14},u_{14})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_5^w,m_5^w,u_5^w)}-(l_{15},m_{15},u_{15})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{16},m_{16},u_{16})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_1^w,m_1^w,u_1^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{12},m_{12},u_{12})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_2^w,m_2^w,u_2^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{22},m_{22},u_{22})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_3^w,m_3^w,u_3^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{32},m_{32},u_{32})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_4^w,m_4^w,u_4^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{42},m_{42},u_{42})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_5^w,m_5^w,u_5^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{52},m_{52},u_{52})\right|\le(k^*,k^*,k^*)\\
\left|\dfrac{(l_6^w,m_6^w,u_6^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{62},m_{62},u_{62})\right|\le(k^*,k^*,k^*)\\
\sum_{j=1}^{6}R(\tilde{w}_j)=1\\
l_j^w\le m_j^w\le u_j^w\\
l_j^w\ge 0\\
\forall j\in N_+
\end{cases}
\end{aligned}
\qquad \text{(B-3)}
$$

$$
\begin{aligned}
&\min k^* \\
&s.t.\begin{cases}
l_1-6.744*u_2\le k^*u_2;l_1-6.744*u_2\ge -k^*u_2;\\
m_1-7.744*m_2\le k^*m_2;m_1-7.744*m_2\ge -k^*m_2;\\
u_1-8.744*l_2\le k^*l_2;u_1-8.744*l_2\ge -k^*l_2;\\
l_1-3.077*u_3\le k^*u_3;l_1-3.077*u_3\ge -k^*u_3;\\
m_1-4.018*m_3\le k^*m_3;m_1-4.018*m_3\ge -k^*m_3;\\
u_1-4.958*l_3\le k^*l_3;u_1-4.958*l_3\ge -k^*l_3;\\
l_1-2.470*u_4\le k^*u_4;l_1-2.470*u_4\ge -k^*u_4;\\
m_1-3.321*m_4\le k^*m_4;m_1-3.321*m_4\ge -k^*m_4;\\
u_1-4.173*l_4\le k^*l_4;u_1-4.173*l_4\ge -k^*l_4;\\
l_1-2.845*u_5\le k^*u_5;l_1-2.845*u_5\ge -k^*u_5;\\
m_1-3.744*m_5\le k^*m_5;m_1-3.744*m_5\ge -k^*m_5;\\
u_1-4.643*l_5\le k^*l_5;u_1-4.643*l_5\ge -k^*l_5;\\
l_1-3.488*u_6\le k^*u_6;l_1-3.488*u_6\ge -k^*u_6;\\
m_1-4.488*m_6\le k^*m_6;m_1-4.488*m_6\ge -k^*m_6;\\
u_1-5.488*l_6\le k^*l_6;u_1-5.488*l_6\ge -k^*l_6;\\
l_3-3.435*u_2\le k^*u_2;l_3-3.435*u_2\ge -k^*u_2;\\
m_3-4.357*m_2\le k^*m_2;m_3-4.357*m_2\ge -k^*m_2;\\
u_3-5.280*l_2\le k^*l_2;u_1-5.280*l_2\ge -k^*l_2;\\
l_4-3.542*u_2\le k^*u_2;l_4-3.542*u_2\ge -k^*u_2;\\
m_4-4.464*m_2\le k^*m_2;m_4-4.464*m_2\ge -k^*m_2;\\
u_4-5.387*l_2\le k^*l_2;u_4-5.387*l_2\ge -k^*l_2;\\
l_5-3.440*u_2\le k^*u_2;l_5-3.440*u_2\ge -k^*u_2;\\
m_5-4.363*m_2\le k^*m_2;m_5-4.363*m_2\ge -k^*m_2;\\
u_5-5.286*l_2\le k^*l_2;u_5-5.286*l_2\ge -k^*l_2;\\
l_6-2.899*u_2\le k^*u_2;l_6-2.899*u_2\ge -k^*u_2;\\
m_6-3.792*m_2\le k^*m_2;m_6-3.792*m_2\ge -k^*m_2;\\
u_6-4.685*l_2\le k^*l_2;u_6-4.685*l_2\ge -k^*l_2;\\
l_1+4*m_1+u_1+l_2+4*m_2+u_2+l_3+4*m_3+u_3+\\
l_4+4*m_4+u_4+l_5+4*m_5+u_5+l_6+4*m_6+u_6=6;\\
l_1\le m_1\le u_1;l_2\le m_2\le u_2;l_3\le m_3\le u_3;\\
l_4\le m_4\le u_4;l_5\le m_5\le u_5;l_6\le m_6\le u_6;\\
l_1\ge 0;l_2\ge 0;l_3\ge 0;l_4\ge 0;l_5\ge 0;l_6\ge 0;\\
k\ge 0
\end{cases}
\end{aligned}
\qquad \text{(B-4)}
$$

Then, we can obtain the following nonlinearly constrained optimization problem (B-4) represented by concrete numbers.

By solving Eq. (B-4), the optimal fuzzy weights of six indicators (C_{11} 'Green goal clarity'; C_{12} 'Green training'; C_{13} 'Green investment'; C_{14} 'Green innovation'; C_{15} 'Green policy responsiveness'; C_{16} 'Green responsibility fulfillment') can be calculated, which are

$\tilde{w}_1^*=(0.365,0.365,0.406);\tilde{w}_2^*=(0.041,0.041,0.048);\tilde{w}_3^*=(0.108,0.129,0.194);$

$\tilde{w}_4^*=(0.136,0.172,0.269);\tilde{w}_5^*=(0.118,0.143,0.221);\tilde{w}_6^*=(0.094,0.111,0.159);$

$\tilde{\xi}^*=(1.193,1.193,1.193)$

(3) Indicator weights of leadership sub-dimension

Eq. (B-5) of the fuzzy relative importance of the leadership sub-dimension can be calculated based on Eq. (6) using the parameters provided in Tables A-4 and A-5.

$$
\begin{aligned}
&\min \tilde{\xi}^{*} \\
&s.t.\begin{cases}
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_1^w,m_1^w,u_1^w)}-(l_{41},m_{41},u_{41})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_2^w,m_2^w,u_2^w)}-(l_{42},m_{42},u_{42})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_3^w,m_3^w,u_3^w)}-(l_{43},m_{43},u_{43})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_4^w,m_4^w,u_4^w)}-(l_{44},m_{44},u_{44})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_5^w,m_5^w,u_5^w)}-(l_{45},m_{45},u_{45})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{46},m_{46},u_{46})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_1^w,m_1^w,u_1^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{16},m_{16},u_{16})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_2^w,m_2^w,u_2^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{26},m_{26},u_{26})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_3^w,m_3^w,u_3^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{36},m_{36},u_{36})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_4^w,m_4^w,u_4^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{46},m_{46},u_{46})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_5^w,m_5^w,u_5^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{56},m_{56},u_{56})\right|\le(k^*,k^*,k^*)\\
\left|\frac{(l_6^w,m_6^w,u_6^w)}{(l_6^w,m_6^w,u_6^w)}-(l_{66},m_{66},u_{66})\right|\le(k^*,k^*,k^*)\\
\sum_{j=1}^{6}R(\tilde{w}_j)=1\\
l_j^w\le m_j^w\le u_j^w\\
l_j^w\ge 0\\
\forall j\in N_+
\end{cases}
\end{aligned}
\qquad \text{(B-5)}
$$

$$
\begin{aligned}
&\min k^{*} \\
&s.t.\begin{cases}
l_4-2.661*u_1\le k^*u_1; l_4-2.661*u_1\ge -k^*u_1;\\
m_4-3.524*m_1\le k^*m_1; m_4-3.524*m_1\ge -k^*m_1;\\
u_4-4.387*l_1\le k^*l_1; u_4-4.387*l_1\ge -k^*l_1;\\
l_4-2.548*u_2\le k^*u_2; l_4-2.548*u_2\ge -k^*u_2;\\
m_4-3.470*m_2\le k^*m_2; m_4-3.470*m_2\ge -k^*m_2;\\
u_4-4.393*l_2\le k^*l_2; u_4-4.393*l_2\ge -k^*l_2;\\
l_4-2.333*u_3\le k^*u_3; l_4-2.333*u_3\ge -k^*u_3;\\
m_4-3.077*m_3\le k^*m_3; m_4-3.077*m_3\ge -k^*m_3;\\
u_4-3.821*l_3\le k^*l_3; u_4-3.821*l_3\ge -k^*l_3;\\
l_4-3.381*u_5\le k^*u_5; l_4-3.381*u_5\ge -k^*u_5;\\
m_4-4.381*m_5\le k^*m_5; m_4-4.381*m_5\ge -k^*m_5;\\
u_4-5.381*l_5\le k^*l_5; u_4-5.381*l_5\ge -k^*l_5;\\
l_4-6.560*u_6\le k^*u_6; l_4-6.560*u_6\ge -k^*u_6;\\
m_4-7.560*m_6\le k^*m_6; m_4-7.560*m_6\ge -k^*m_6;\\
u_4-8.560*l_6\le k^*l_6; u_4-8.560*l_6\ge -k^*l_6;\\
l_1-4.256*u_6\le k^*u_6; l_1-4.256*u_6\ge -k^*u_6;\\
m_1-5.256*m_6\le k^*m_6; m_1-5.256*m_6\ge -k^*m_6;\\
u_1-6.256*l_6\le k^*l_6; u_1-6.256*l_6\ge -k^*l_6;\\
l_2-4.310*u_6\le k^*u_6; l_2-4.310*u_6\ge -k^*u_6;\\
m_2-5.280*m_6\le k^*m_6; m_2-5.280*m_6\ge -k^*m_6;\\
u_2-6.250*l_6\le k^*l_6; u_2-6.250*l_6\ge -k^*l_6;\\
l_3-3.923*u_6\le k^*u_6; l_3-3.923*u_6\ge -k^*u_6;\\
m_3-4.923*m_6\le k^*m_6; m_3-4.923*m_6\ge -k^*m_6;\\
u_3-5.923*l_6\le k^*l_6; u_3-5.923*l_6\ge -k^*l_6;\\
l_5-3.202*u_6\le k^*u_6; l_5-3.202*u_6\ge -k^*u_6;\\
m_5-4.202*m_6\le k^*m_6; m_5-4.202*m_6\ge -k^*m_6;\\
u_5-5.202*l_6\le k^*l_6; u_5-5.202*l_6\ge -k^*l_6;\\
l_1+4*m_1+u_1+l_2+4*m_2+u_2+l_3+4*m_3+u_3+\\
l_4+4*m_4+u_4+l_5+4*m_5+u_5+l_6+4*m_6+u_6=6;\\
l_1\le m_1\le u_1; l_2\le m_2\le u_2; l_3\le m_3\le u_3;\\
l_4\le m_4\le u_4; l_5\le m_5\le u_5; l_6\le m_6\le u_6;\\
l_1\ge 0; l_2\ge 0; l_3\ge 0; l_4\ge 0; l_5\ge 0; l_6\ge 0;\\
k\ge 0
\end{cases}
\end{aligned}
\qquad \text{(B-6)}
$$

Then, we can obtain the following nonlinearly constrained optimization problem (B-6) represented by concrete numbers. By solving Eq. (B-6), the optimal fuzzy weights of six indicators (C_{21} 'EMS adoption'; C_{22} 'ESG rating'; C_{23} 'Employee exchange depth'; C_{24} 'Enterprise exchange degree'; C_{25} 'Green investors'; C_{26} 'Green bond issuance') can be calculated, which are

$$
\begin{aligned}
&\tilde{w}_1^{*}=(0.123,0.165,0.194); \tilde{w}_2^{*}=(0.125,0.166,0.193); \tilde{w}_3^{*}=(0.109,0.152,0.181);\\
&\tilde{w}_4^{*}=(0.315,0.370,0.386); \tilde{w}_5^{*}=(0.079,0.121,0.152); \tilde{w}_6^{*}=(0.039,0.042,0.042);\\
&\tilde{\xi}^{*}=(1.312,1.312,1.312)
\end{aligned}
$$

(4) Indicator weights of sustainable sub-dimension

Eq. (B-7) of the fuzzy relative importance of the sustainable sub-dimension can be calculated based on Eq. (6) using the parameters provided in Tables A-6 and A-7.

$$\min \tilde{\xi}^*$$

$$s.t.\begin{cases}
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_1^w, m_1^w, u_1^w)} - (l_{51}, m_{51}, u_{51})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_2^w, m_2^w, u_2^w)} - (l_{52}, m_{52}, u_{52})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{53}, m_{53}, u_{53})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_4^w, m_4^w, u_4^w)} - (l_{54}, m_{54}, u_{54})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_5^w, m_5^w, u_5^w)} - (l_{55}, m_{55}, u_{55})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{56}, m_{56}, u_{56})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_1^w, m_1^w, u_1^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{16}, m_{16}, u_{16})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_2^w, m_2^w, u_2^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{26}, m_{26}, u_{26})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_3^w, m_3^w, u_3^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{36}, m_{36}, u_{36})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{46}, m_{46}, u_{46})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{56}, m_{56}, u_{56})\right| \le (k^*, k^*, k^*) \\
\left|\frac{(l_6^w, m_6^w, u_6^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{66}, m_{66}, u_{66})\right| \le (k^*, k^*, k^*) \\
\sum_{j=1}^{6} R(\tilde{w}_j) = 1 \\
l_j^w \le m_j^w \le u_j^w \\
l_j^w \ge 0 \\
\forall j \in N_+
\end{cases} \tag{B-7}$$

$$\min k^*$$

$$s.t.\begin{cases}
l_5 - 2.845*u_1 \le k^* u_1; l_5 - 2.845*u_1 \ge -k^* u_1; \\
m_5 - 3.845*m_1 \le k^* m_1; m_5 - 3.845*m_1 \ge -k^* m_1; \\
u_5 - 4.845*l_1 \le k^* l_1; u_5 - 4.845*l_1 \ge -k^* l_1; \\
l_5 - 2.685*u_2 \le k^* u_2; l_5 - 2.685*u_2 \ge -k^* u_2; \\
m_5 - 3.685*m_2 \le k^* m_2; m_5 - 3.685*m_2 \ge -k^* m_2; \\
u_5 - 4.685*l_2 \le k^* l_2; u_5 - 4.685*l_2 \ge -k^* l_2; \\
l_5 - 2.702*u_3 \le k^* u_3; l_5 - 2.702*u_3 \ge -k^* u_3; \\
m_5 - 3.631*m_3 \le k^* m_3; m_5 - 3.631*m_3 \ge -k^* m_3; \\
u_5 - 4.560*l_3 \le k^* l_3; u_5 - 4.560*l_3 \ge -k^* l_3; \\
l_5 - 1.369*u_4 \le k^* u_4; l_5 - 1.369*u_4 \ge -k^* u_4; \\
m_5 - 2.196*m_4 \le k^* m_4; m_5 - 2.196*m_4 \ge -k^* m_4; \\
u_5 - 3.024*l_4 \le k^* l_4; u_5 - 3.024*l_4 \ge -k^* l_4; \\
l_5 - 6.083*u_6 \le k^* u_6; l_5 - 6.083*u_6 \ge -k^* u_6; \\
m_5 - 7.083*m_6 \le k^* m_6; m_5 - 7.083*m_6 \ge -k^* m_6; \\
u_5 - 8.083*l_6 \le k^* l_6; u_5 - 8.083*l_6 \ge -k^* l_6; \\
l_1 - 3.333*u_6 \le k^* u_6; l_1 - 3.333*u_6 \ge -k^* u_6; \\
m_1 - 4.333*m_6 \le k^* m_6; m_1 - 4.333*m_6 \ge -k^* m_6; \\
u_1 - 5.333*l_6 \le k^* l_6; u_1 - 5.333*l_6 \ge -k^* l_6; \\
l_2 - 3.548*u_6 \le k^* u_6; l_2 - 3.548*u_6 \ge -k^* u_6; \\
m_2 - 4.518*m_6 \le k^* m_6; m_2 - 4.518*m_6 \ge -k^* m_6; \\
u_2 - 5.488*l_6 \le k^* l_6; u_2 - 5.488*l_6 \ge -k^* l_6; \\
l_3 - 2.958*u_6 \le k^* u_6; l_3 - 2.958*u_6 \ge -k^* u_6; \\
m_3 - 3.851*m_6 \le k^* m_6; m_3 - 3.851*m_6 \ge -k^* m_6; \\
u_3 - 4.744*l_6 \le k^* l_6; u_3 - 4.744*l_6 \ge -k^* l_6; \\
l_4 - 3.524*u_6 \le k^* u_6; l_4 - 3.524*u_6 \ge -k^* u_6; \\
m_4 - 4.446*m_6 \le k^* m_6; m_4 - 4.446*m_6 \ge -k^* m_6; \\
u_4 - 5.369*l_6 \le k^* l_6; u_4 - 5.369*l_6 \ge -k^* l_6; \\
l_1 + 4*m_1 + u_1 + l_2 + 4*m_2 + u_2 + l_3 + 4*m_3 + u_3 + \\
l_4 + 4*m_4 + u_4 + l_5 + 4*m_5 + u_5 + l_6 + 4*m_6 + u_6 = 6; \\
l_1 \le m_1 \le u_1; l_2 \le m_2 \le u_2; l_3 \le m_3 \le u_3; \\
l_4 \le m_4 \le u_4; l_5 \le m_5 \le u_5; l_6 \le m_6 \le u_6; \\
l_1 \ge 0; l_2 \ge 0; l_3 \ge 0; l_4 \ge 0; l_5 \ge 0; l_6 \ge 0; \\
k \ge 0
\end{cases} \tag{B-8}$$

Then, we can obtain the following nonlinearly constrained optimization problem (B-8) represented by concrete numbers.

By solving Eq. (B-8), the optimal fuzzy weights of six indicators (C_{31} 'Product R&D potential'; C_{32} 'Digital transformation capacity'; C_{33} 'Executive green consciousness'; C_{34} 'Corporate internal control'; C_{35} 'Enterprise growth'; C_{36} 'ROI') can be calculated, which are

$\tilde{w}_1^* = (0.099, 0.121, 0.195); \tilde{w}_2^* = (0.103, 0.129, 0.216); \tilde{w}_3^* = (0.107, 0.132, 0.214);$
$\tilde{w}_4^* = (0.197, 0.219, 0.255); \tilde{w}_5^* = (0.321, 0.321, 0.360); \tilde{w}_6^* = (0.039, 0.039, 0.046);$
$\tilde{\xi}^* = (1.201, 1.201, 1.201)$

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