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How does open innovation promote circular economy practices? Evidence from Chinese listed companies

Xingmin Yin [a], Yun Jin [a], Zhou Li [b], Yulin Liu [c,*]

[a] School of Economics, Ocean University of China, Qingdao 266100, China
[b] School of International Business and Management, Sichuan International Studies University, Chongqing 400031, China
[c] Center of Public Economy & Public Policy Research, Chongqing University, Shazheng Street, Shapingba District, Chongqing 400044, China

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ABSTRACT

Although firms contend with multiple challenges in implementing circular economy (CE) practices, open innovation (OI) can be an effective collaborative strategy for firms to overcome technological and informational barriers and achieve CE objectives. Using data from A-share and Science and Technology Innovation Board (STAR Market) listed companies in China from 2003 to 2022, we employ a two-way fixed effects model to examine the impact of OI on firms' CE practices. The empirical results indicate that OI significantly promotes CE practices, influencing these practices through mechanisms such as trade credit provision, green patent accumulation, and enhanced information exchange. Moreover, government CE policies can strengthen the effect of OI on CE practices. Additionally, intercompany OI has a stronger positive impact on CE practices compared with intracompany and cooperative OI. The effects of OI and the moderating influence of CE policies are more pronounced in the eastern region, which is likely driven by superior industrialization in the region. These findings clarify the relationship between OI and CE practices to advance global CE practices. Future research could explore broader datasets, adopt alternative OI indicators, and conduct cross-country comparisons to further expand this research.

Introduction

As extreme climate impacts economic, social, and environmental development, countries are increasingly exploring new green economic models to avoid the high emissions and pollution challenges of traditional crude economic growth models (Yuan & Pan, 2023; Yuana et al., 2024). The circular economy (CE) concept is based on the principle of "reduce, reuse, and recycle" (Geissdoerfer et al., 2017), meaning that goods are not discarded after single use but recycled and reused as much as possible (Stucki et al., 2023). It is widely acknowledged that major economies worldwide generally consider CE development as a possible approach for promoting pollution prevention and comprehensive waste utilization to achieve mutually beneficial outcomes for the environment and the economy. Considering that China is one of the most populous countries in the world, the nation faces enormous resource pressure and environmental challenges. The Chinese government has been actively promoting CE development, considering it an important path to achieving sustainable development. In recent years, China has developed a series of policies to encourage individuals and firms to take action, reduce resource waste, and improve resource utilization efficiency. For instance, the Circular Economy Promotion Law, implemented in 2009, is a key regulatory framework intended to promote resource recycling and sustainable economic practices across various sectors in China (Chen & Dagestani, 2023).

As the main body and key force for advancing CE development, firms face many challenges in integrating CE practices (Puglia et al., 2024; Stucki et al., 2023; Yang et al., 2023; Zhang et al., 2023). Previous studies have primarily conducted extensive research on the factors that affect CE practices from macroperspective and microperspective. At the macrolevel, social and cultural factors and government CE policies are closely related to CE practices (Eversberg & Fritz, 2022; González-Moreno et al., 2024; Shang et al., 2022). Social and cultural factors such as individualism, an innovation-driven mindset (Eversberg & Fritz, 2022), and the public's recognition of the CE (González-Moreno et al., 2024), have a crucial influence on shaping CE practices. For instance, higher societal acceptance of CE principles can drive consumer demand for sustainable products and encourage firms to adopt circular business models (González-Moreno et al., 2024). At the microlevel,

* Corresponding author.
E-mail address: lylmx@cqu.edu.cn (Y. Liu).

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firms' financial conditions (de Oliveira Neto et al., 2022; Meili & Stucki, 2023), the strength of received government subsidies (Lahane & Kant, 2021; Larrain et al., 2024), private investment (Al-Omoush et al., 2022), and the technology and information exchange levels (Stucki et al., 2023) have received considerable attention. Currently, the main barriers to firms' engagement in CE practices have been demonstrated at the microlevel, particularly in terms of financial constraints and knowledge reserves (Meili & Stucki, 2023; Wang et al., 2023). Collaboration between companies (i.e., open innovation; OI) is a potential approach to overcoming the significant technological and informational barriers related to the requirement for new technologies, knowledge, and product development when practicing the CE.

OI has been defined as an important type of technological and informational exchange collaboration between firms (Zhang et al., 2023). The concept refers to firms' leveraging external and internal ideas and mobilizing internal and external resources to enhance technological capabilities (Wang et al., 2023). The boundaries of OI have been expanded to a purposeful distributed innovation process that relies on information flow across company boundaries (Chesbrough & Bogers, 2014). OI can enhance firms' competitive advantages. Studies have demonstrated that OI brings significant benefits to firms by promoting new product development, shortening the product development cycle, and accelerating firms' growth (Hutton et al., 2024; Toroslu et al., 2023). OI also has a significant influence on improving firms' performance. Research has shown that it can enhance firms' export, innovation, business, and financial performance (Ogiemwonyi et al., 2023; Schäper et al., 2023). As environmental challenges become increasingly urgent, scholars have also begun to explore the impact of OI on companies' green transformation. Studies have indicated that open eco-innovation promotes renewable energy and green technology development and application through participation and collaboration in innovation networks (Csedő et al., 2023; Roh et al., 2021). OI promotes technological advancement and significantly improves green total factor productivity by integrating external knowledge and optimizing internal resources to promote efficient energy use (Wang et al., 2023).

Several studies have demonstrated the correlation between OI and CE practices, indicating that OI can promote corporate practices in the CE. Companies must frequently communicate with stakeholder groups (customers, suppliers, academia, and the community) to overcome internal capability limitations and integrate CE practices (Fang et al., 2024; Jesus & Jugend, 2023; Perotti et al., 2024). Furthermore, firms can discover and apply ready-made circular solutions through collaborations with lead green transformation companies, reducing the risks associated with adopting CE practices (Calabrese et al., 2024; Kennedy et al., 2017; Leonidou et al., 2024). Furthermore, some scholars have argued that CE practices promote OI. Environmental economic practices have a positive impact on enterprises' innovation activities; however, due to limited research and development (R&D) capabilities, small and medium-sized enterprises (SMEs) often adopt OI to acquire existing knowledge and capabilities to reduce innovation risks (Sarango-Lalangui et al., 2023). The research on the relationship between OI and CE practices has been increasing. However, the underlying influencing mechanisms remain unclear, and existing studies have predominantly employed case study methods, often focusing on limited sample sizes (Calabrese et al., 2024; Perotti et al., 2024). Further empirical research is essential to establishing a more comprehensive understanding of how OI drives CE adoption across different contexts.

Building on the existing literature, this study offers a comprehensive understanding of how firms' OI influences CE practices and the role of government policies in this relationship. Specifically, we first develop a theoretical framework to analyze the transmission mechanisms through which OI promotes CE practices, exploring the three key pathways of commercial credit acquisition, green knowledge reserves, and information exchange. Second, we conduct an empirical analysis using unbalanced panel data from listed companies on the A-shares and Science and Technology Innovation Board (STAR Market) in China from 2003 to 2022. Using robust econometric methods, we present empirical evidence on the influencing mechanisms and examine the moderating effect of CE policies. Finally, we further deepen our analysis by considering firm and regional heterogeneity to investigate how different types of OI categorized based on firm boundaries exert diverse impacts on CE practices. We also explore the conditions under which government CE policies amplify or constrain the effectiveness of OI in promoting sustainable business practices.

This study makes three notable contributions to the literature. First, by integrating theoretical analysis with empirical verification, we offer novel insights into the mechanisms through which OI facilitates CE practices; a topic that has been relatively underexplored. Second, we extend the understanding of policy interventions by systematically examining the moderating role of government CE policies, providing valuable insights regarding the conditions that can enhance or hinder their effectiveness. Third, unlike previous studies that have primarily used case studies or focused on specific industries, our research covers a broad sample of listed firms across various sectors (excluding financial firms), which enhances the generalizability of our findings. These contributions advance academic investigations on OI and CE practices and have valuable policy implications for fostering sustainable industrial transformation.

The remainder of this paper is organized as follows. Section 2 presents our theoretical analysis and hypotheses. Section 3 details the study's methodology. Section 4 presents the analysis and results, Section 5 discusses the results, and Section 6 provides the conclusion, covering key findings, contributions and implications, limitations, and directions for future research.

Theoretical framework and hypotheses

Concept definitions

OI

OI refers to the use of companies' internal and external innovations to improve the innovation process while also making internal knowledge and technology available to external market environments. As this innovation activity continues to develop, the concept of OI encompasses internal and external collaboration and ecosystems to drive business model and service innovation development (Chesbrough, 2017). OI has evolved to include new models such as innovation ecosystems (Zhang et al., 2025) and crowdfunding (Dabbous et al., 2024). Traditional OI refers to knowledge flow that primarily occurs across firm boundaries, encompassing inbound, outbound, and coupled processes (Chesbrough, 2017). The inbound process emphasizes identifying and absorbing external knowledge to enhance internal innovation capabilities, which is also known as inbound OI (Bianchi et al., 2016). Correspondingly, the outbound process refers to pushing internal innovation results to the external environment (outbound OI), which can be achieved through technology licensing agreements, startups, and other processes (Enkel et al., 2009). Coupled processes refer to combined inbound and outbound OI to develop innovations and achieve commercialization through collaborations and partnerships between companies and stakeholders (Enkel et al., 2009).

CE

CE is a concept for promoting sustainable development that originated from industrial ecology that is intended to advance more efficient resource utilization, waste reduction, and cleaner technology adoption (Andersen, 2007). CE emphasizes reduce, reuse, and recycle principles to achieve closed-loop cycles of products, technologies, and biology by maintaining products, components, and materials at high-value levels (Geissdoerfer et al., 2017). CE practices can be implemented at the microlevel, mesolevel, and macrolevel (Kristensen & Mosgaard, 2020). At the microlevel, firms focus on self-improvement and business development, influencing profitability and reputations through engaged and publicized environmental management practices. Firms can use recycled materials, design products for disassembly, and implement take-back schemes to recover used products for remanufacturing (Fang et al., 2024). At the mesolevel, firms use information systems to facilitate resource exchange while promoting regional economic and natural environment development. A notable example is agri-food industrial parks that implement CE principles by using food waste and byproducts to generate new value (Atanasovska et al., 2022). At the macrolevel, the CE involves a broader geographical scope, with governments implementing public policies and systems to promote the development of environmental strategies such as the Extended Producer Responsibility (EPR) policy (Kunz et al., 2018).

Hypotheses development

As a cooperative paradigm, OI can provide possible solutions to overcome the barriers firms face in adopting CE practices by promoting internal and external cooperation and knowledge flow. First, OI can facilitate close collaboration among stakeholders in government, social institutions, and communities. By establishing an OI ecosystem, all parties can jointly explore the challenges and opportunities of CE practices to formulate and implement innovative solutions (Lu & Chesbrough, 2022; Schäper et al., 2023). Active participation of government departments and communities in CE practices has a key influence on providing policy support and market guidance for firms, promoting the practical implementation of the CE concept. Additionally, OI promotes cross-boundary knowledge sharing and flow, providing firms with more convenient access to external knowledge and technology (Ogiemwonyi et al., 2023; Srisathan et al., 2023). Firms can obtain the latest research results and cutting-edge technologies in the industry more easily through OI channels, accelerating the implementation of CE practices and improving the efficiency of such practices. OI also provides firms with the ability to respond more flexibly and rapidly to market demands and changes (Csedő et al., 2023; Jang & von Zedtwitz, 2023). Firms can obtain market feedback more quickly, improve and optimize existing CE practices, and develop such practices to better meet market demands. However, despite these advantages, in the context of the CE, OI also introduces potential challenges. Firms engaging in OI may risk exposing proprietary green technologies to competitors, which could weaken their long-term market position (Fang et al., 2024). Moreover, supply chain partners may have differing sustainability goals, which can make it difficult to align strategies for CE implementation (Leonidou et al., 2024; Pattanayak et al., 2024). Despite these challenges, the overall benefits of OI in driving CE practices tend to outweigh the risks (Csedő et al., 2023; Ogiemwonyi et al., 2023). Based on the above theoretical analysis, we propose Hypothesis 1.

H1. OI promotes corporate adoption of CE practices.

Companies that adopt OI strategies typically engage in close communication and collaboration with various stakeholders. This interaction reduces information asymmetry, particularly within supply chain networks (Cao et al., 2022). Through ongoing communication and cooperation, companies and stakeholders can share information, resources, and needs more easily, minimizing moral hazards in partnerships and fostering mutual trust (Chiu & Lin, 2022; Han et al., 2021). Establishing and maintaining strong trust relationships when implementing a CE strategy is crucial. For example, close collaboration between upstream and downstream companies is necessary in the production of recyclable products to effectively mitigate various risks in the production process (Liu et al., 2023). Upstream suppliers must trust downstream manufacturers to handle and use recyclable materials appropriately. Building trust enables upstream suppliers to actively cooperate with downstream partners to explore methods for increasing material recycling rates, reducing waste, and optimizing CE production processes. Furthermore, such trust is reflected in increased access to commercial credit for businesses. This indicates that suppliers are more willing to assume the risks associated with delayed payments from trusted companies (Xiu et al., 2023). Therefore, OI enables companies to secure more trade credit. In the resource-based view (RBV), firms' competitive advantages stem from unique resources and capabilities (Barney, 1991). Interest-free funds can reduce financing costs, enhance cash flow, and improve operational flexibility, enabling companies to maintain a strong financial position to advance CE initiatives (Lu & Chesbrough, 2022; Schäper et al., 2023). Based on this theoretical analysis, we propose Hypothesis 2a.

H2a. OI promotes corporate CE practices by enhancing access to commercial credit.

As a dynamic and flexible model, OI provides companies with extensive opportunities to acquire green patents, particularly in a context in which environmental challenges are escalating and green technologies are becoming increasingly complex (Ogiemwonyi et al., 2023; Roh et al., 2021). Companies can purchase green patents, obtain licensing from universities or other research institutions, or collaborate with complementary firms in collaborative innovation, creating valuable opportunities to expand their green capabilities and knowledge reserves (Roh et al., 2021). In this process, companies do more than simply acquire green patents; they gain deep insights into the critical skills and knowledge required to obtain patents through collaboration with patent partners (Zhao et al., 2022). This collaboration also helps firms develop capabilities to develop new patented technologies, enhancing R&D capabilities (Figueiredo et al., 2020). Companies can gain a deeper understanding of the green technology sector and stay abreast of the latest trends and developments in green innovation, expanding their expertise and technological strength in the field (Leitão et al., 2024; Zeng et al., 2022). Therefore, OI can significantly enhance a company's green knowledge reserves. According to the RBV (Barney, 1991), green knowledge reserves are a critical strategic resource that establishes a foundation for sustainable competitive advantage. A well-developed green knowledge reserve provides a solid base for CE implementation. Firms with extensive green knowledge can optimize resource efficiency, develop recyclable and eco-friendly products, and adopt closed-loop production systems (Ai et al., 2024). We propose Hypothesis 2b based on the above theoretical analysis.

H2b. OI promotes corporate CE practices by increasing green knowledge reserves.

Within the CE framework, a company's core goals include resource conservation and reuse, which can be achieved through continuously optimizing production processes and product life cycles to ensure efficient resource circulation. The OI model encourages companies to actively share information and knowledge with supply chain partners, customers, and other stakeholders, providing them with opportunities to gain deeper insights into market demands and trends. Companies can access comprehensive market information and gain a deeper understanding of consumers' needs and preferences through engagement and collaboration with external partners (Fisher et al., 2024). Stakeholder theory highlights the crucial role of various stakeholders such as suppliers, customers, and regulatory bodies in shaping firms' strategic initiatives (Ozdemir et al., 2023). The process of information sharing and knowledge exchange enables companies to design and produce products that meet market demands more accurately, enhancing their adaptability and competitiveness (Jang & von Zedtwitz, 2023). OI also equips companies with the ability to identify and swiftly adapt to environmental changes, which is crucial in CE practices. In the OI framework, companies can flexibly acquire external information and respond promptly to meet evolving market demands and environmental trends (Al-Omoush et al., 2024). This agility in recognition and adaptation enables companies to seize opportunities, effectively overcome challenges, and maintain competitiveness. Companies should establish flexible innovation mechanisms and continuously adjust CE models to adapt to the rapidly changing market environment (Guo et al., 2023;

Vasi et al., 2024). Based on the above theoretical analysis, we propose Hypothesis 2c.

H2c. OI facilitates corporate CE practices by enhancing information exchange.

CE practices are characterized by long payback periods, high market demand uncertainty, and substantial investment costs. As businesses often find it challenging to transition from a linear approach to a CE model independently, government CE policies have a significant influence on encouraging companies' active engagement in CE practices (Chenavaz & Dimitrov, 2024; Puglia et al., 2024). For example, governments can implement incentive programs to support companies in designing and producing recyclable products. These incentives may include subsidies or tax reductions for businesses investing in CE processes. Another important policy tool is the EPR policy, which encourages companies to consider their products' end-of-life stage during the design phase to make them easier to reuse, repair, or recycle, fostering innovation in product design and waste management (Kunz et al., 2018). Moreover, CE policies also influence consumer behavior (Hartley et al., 2023; Yuana et al., 2024). For example, governments may offer subsidies to consumers who purchase recyclable products, encouraging them to buy recycled goods and actively participate in repair and reuse activities. Therefore, government CE policies can guide firms to engage in OI within the CE domain by providing incentives and regulatory frameworks and stimulating demand for recyclable products (Puglia et al., 2024). Based on the above analysis, we propose Hypothesis 3.

H3. CE policies positively moderate the relationship between OI and corporate CE practices.

Based on Hypotheses 1, 2a, 2b, 2c, and 3, the theoretical framework of this paper is illustrated in Fig. 1.

Methods

Variable definitions and descriptions

Dependent variable: CE practices

Previous research has employed a variety of methods to measure corporate CE practices such as surveys (Meili & Stucki, 2023; Stucki et al., 2023), content analysis (Yuan & Pan, 2023), and text analysis (Alkaraan et al., 2023; Chen & Dagestani, 2023). Considering the availability and objectivity of the data, we employ text analysis to evaluate corporate practices in the CE.

Independent variable: OI

Firms' innovation is often reflected in patent acquisition (Belderbos et al., 2014). Moreover, patent acquisition is an optimal variable to comprehensively study OI across diverse industries due to high data availability and standardization (Walsh et al., 2016). Accordingly, based on the OI concept, we consider listed companies' joint patent publication as representative of OI (Arora et al., 2016). Based on the varying scopes of corporate boundaries and the characteristics of patent data, we classify corporate OI into three types. First, intracompany OI, which involves multiple firms within the same publicly listed company jointly disclosing patents and is denoted as Open_innov_in_comp. Second, intercompany OI, which involves firms from different publicly listed companies jointly disclosing patents and is denoted as Open_innov_bet_comp. Third, cooperative innovation, which involves a subsidiary of one publicly listed company jointly disclosing patents with an affiliated company of another publicly listed company, which is denoted as Open_innov_with_comp.

Mediating variables

- Trade credit acquisition. Trade credit enables a party to delay payment solely based on its existing creditworthiness and reflects the trust between upstream and downstream companies in a supply chain. The amount that a company delays paying its suppliers is reflected in its financial statements as accounts payable. Referencing previous studies (Ding et al., 2023; Gan et al., 2024), we use the ratio of accounts payable to total liabilities to measure firms' trade credit access.
- Green knowledge reserves. Green patents refer to patents related to environmental protection, sustainable development, and similar concerns, including technologies in environmental protection, clean energy, and CE. We use the number of green patents a company holds to reflect its actual performance and capability in green technology innovation (Ai et al., 2024). Since some companies do not have green patents, we use the natural logarithm of the number of green patents plus one to measure firms' green knowledge acquisition.
- Information exchange. Information exchange between a company and its external environment encompasses knowledge and market information exchange. Such exchange reflects a firm's innovation capacity, competitive advantages, and ability to adapt to market changes. We measure knowledge exchange by the number of citations of a listed company's patents, and quantify market information exchange by the coefficient of variation in the company's annual R&D intensity (R&D expenditure/revenue), capital intensity (capital expenditure/revenue), and advertising intensity (advertising expenditure/revenue) (Yang et al., 2023).

Moderating variable: CE policy

CE policies include regulatory, voluntary, and economic incentive policies (Chenavaz & Dimitrov, 2024). China has produced numerous policy documents related to developing a CE, and specific policies must be aligned with China's practical circumstances. The Circular Economy

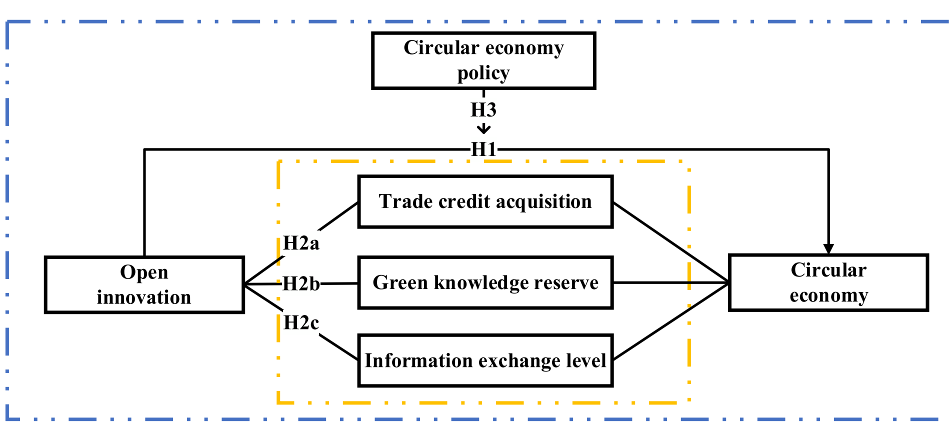

Fig. 1. Framework.

Pilot City Initiative is intended to integrate CE principles into industry, agriculture, services, and urban infrastructure development by promoting CE production methods and green lifestyles across all stages of production, distribution, and consumption (Luo & Leipold, 2022; Ma et al., 2022). This policy is expected to have a significant impact in the regions where it is implemented. Therefore, we construct a dummy variable to measure the impact of CE policies on firms, indicating whether the province where a company is located is participating in the Circular Economy Pilot City Initiative.

Control variables

Referencing previous research (Fang et al., 2024; Yuan & Pan, 2023), we introduce the following control variables that may influence corporate practices in the CE into our model.

- Firm size (SIZE), measured by the natural logarithm of total assets;
- Firm age (AGE), measured by the number of years since firms' establishment to the observation year;
- Degree of Combined Leverage(DCL), represented by the ratio of the change in net profit to that of main business revenue;
- Cash flow status (CFO), expressed as the ratio of net cash flow from operating activities to total assets;
- Total asset turnover, measured by the ratio of operating revenue to total assets;
- Board size (BOARD), measured by the natural logarithm of the number of board members;
- CEO duality (DUAL), indicating whether the CEO and board chair are the same person (1 if yes, 0 if no);
- Big Four audit (AUDIT), indicating whether the annual report is audited by a Big Four accounting firm (Deloitte, Ernst & Young, KPMG, and PricewaterhouseCoopers) (1 if yes, 0 if no).

Methods for generating key variables

Dependent variable: CE practices

First, since all textual materials used in this study are in Chinese, we preprocess the textual materials using Jieba, which is a widely adopted Chinese word segmentation library. This step is essential because, unlike English, Chinese texts do not have natural word boundaries. Following segmentation, we employ Latent Dirichlet Allocation (LDA) topic modeling to extract key themes related to CE practices from policy documents. LDA is a probabilistic model that assumes each document consists of multiple topics, with each topic represented by a set of keywords. Analyzing a collection of 11 authoritative policy documents from institutions such as the State Council, the National Development and Reform Commission, and the State Environmental Protection Administration, we identify 13 core topic words that encapsulate critical aspects of CE practices. The resulting topic words include CE, greening, renewable resources, clean production, remanufacturing, comprehensive utilization, bulk solid waste, circular transformation, recycling, comprehensive resource utilization, recovery, discarded materials, and resource recovery. To address the concern that companies in different provinces may use varying terminologies to describe similar CE practices, we employ Word2Vec; a machine learning model that identifies semantic relationships between words. We train the Word2Vec model on central and provincial government work reports to expand our initial set of 13 keywords into a more comprehensive dictionary of 55 terms closely associated with CE practices. Finally, we count the frequency of the 55 CE-related terms in each company's report, using it as an indicator of firms' CE engagement.

Independent variable: OI

First, we establish a database to map each listed company's stock code to its official name, as well as the names of firms' subsidiaries and joint ventures. Next, we individually match the applicant names for each patent against this database. If a patent has only one applicant but matches two different listed company codes, this indicates that the application represents a joint venture between two listed companies, and we classify the patent as cooperative OI. For patents with two or more applicants, if all applicants match only one listed company code, the patent is categorized as intercompany OI. However, if different applicants match different listed company codes, the patent is classified as intracompany OI. Finally, we aggregate the annual OI data for each listed company. As many companies did not engage in joint patent applications and zero cannot be logarithmically transformed, we use the logarithm of the number of joint patents plus one as an indicator of OI for all sample companies.

Data collection and sampling

The data used in this study primarily include patent data and firm-level data. The patent data are sourced from the China National Knowledge Infrastructure full-text patent database and include fields such as patent application numbers, publication dates, and applicants for 5.54 million invention patents. After filtering the applicant field for listed companies' names, subsidiaries, and joint ventures, we identified 1,139,691 patents that could be attributed to our sample of listed companies. Firm-level data are obtained from the China Stock Market & Accounting Research database, including basic company information, financial statements, and equity structure information. We obtain companies' annual report texts from the Cninfo website and process them using Jieba for text segmentation. After organizing the data, we performed the following data cleaning steps. (1) Excluding listed companies in the financial and insurance sectors; (2) excluding samples with ST, *ST, and PT markers; (3) matching by stock code and year, we integrate CE practices, OI, and control variables, constructing an unbalanced panel dataset with 40,219 sample observations from 2003 to 2022.Table 1 presents the correlation matrix and descriptive statistics of the data.

Model specification

Benchmark regression model

Based on the theoretical analysis and hypotheses in Section 2, we construct a two-way fixed effects (TWFE) model to examine the impact of OI on corporate CE practices. The specific model is as follows:

$$CEWF_{it} = \beta_0 + \beta_1 Open\_innov_{it} + \sum \beta_n ContVars_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (1)$$

where the dependent variable ($CEWF_{it}$) represents the firm's CE practices. The key independent variable ($Open\_innov_{it}$) denotes the firm's OI. $ContVars_{it}$ represents the previously introduced set of control variables, λ_i denotes individual fixed effects (FEs), η_t denotes year FEs, and ε_{it} is the error term.

Mediating effect model

We use the following model to examine the mediating effects of trade credit acquisition, green knowledge reserves, and information exchange.

$$CEWF_{it} = \beta_0 + \beta_1 Open\_innov_{it} + \sum \beta_n ContVars_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (2)$$

$$M_{it} = \beta_0 + \beta_1 Open\_innov_{it} + \sum \beta_n ContVars_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (3)$$

where M_{it} represents the mediating variables of trade credit acquisition (CTA), green knowledge reserves (GKRs), and information exchange level as mediator variables.

Table 1
Descriptive statistics and correlation matrix.

	Variables	1	2	3	4	5	6	7	8	9	10
1	CEP	1.000									
2	Open_innov	0.186*	1.000								
3	SIZE	0.252*	0.292*	1.000							
4	AGE	0.188*	0.132*	0.263*	1.000						
5	DCL	0.030*	-0.018*	0.058*	0.008*	1.000					
6	CFO	0.018*	0.029*	0.052*	0.0000	-0.068*	1.000				
7	TAT	0.008	0.011*	0.034*	-0.024*	-0.022*	0.114*	1.000			
8	BOARD	-0.010*	0.033*	0.195*	-0.076*	0.069*	0.047*	0.036*	1.000		
9	DUAL	-0.010*	0.014*	-0.138*	-0.021*	-0.062*	-0.012*	-0.054*	-0.191*	1.000	
10	AUDIT	0.023*	0.138*	0.320*	0.015*	-0.007	0.071*	0.024*	0.095*	-0.057*	1.000
Mean	10.397	0.371	22.044	16.637	2.415	0.052	0.6345	2.143	0.268	0.061	
SD	16.377	0.972	1.320	6.422	2.921	0.071	0.4294	0.202	0.443	0.240	
Min	0.0000	0.000	15.417	0.000	0.877	-0.163	0.0741	1.609	0.000	0.000	
Max	97.000	9.095	28.606	62.000	21.347	0.258	2.5182	2.708	1.000	1.000	

* Note. indicate that the bilateral test is significant at 5 %.

Moderating effect model

$$CEWF_{it} = \beta_0 + \beta_1 Open\_innov_{it} + \beta_2 Policy_{it} + \beta_3 Policy_{it} \times Open\_innov_{it} + \sum \beta_n ContVars_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (4)$$

where $Policy_{it}$ denotes the moderating variable of OI policy.

Analysis and results

Benchmark regression

We used a TWFE model to assess the impact of OI on corporate CE practices. The regression results are presented in Table 2 Column (1) presents the regression results including only control variables, without considering FEs. Columns (2) and (3) show the regression results with individual and year FEs, respectively. The results indicate that the coefficient for OI is positive and significant at the 1 % level, indicating that OI enhances corporate CE practices.

Table 2
Benchmark regression results.

Variables	(1) CEP	(2) CEP	(3) CEP
Open_innov	1.3450***	1.1023***	1.0302***
	(0.0761)	(0.0748)	(0.1734)
CFO	1.9544**	1.7742**	2.2639**
	(0.8300)	(0.8222)	(1.0596)
BOARD	-0.6888	-0.2799	-0.5375
	(0.4237)	(0.4178)	(0.8373)
TAT	0.9470***	0.6509***	0.6863
	(0.2118)	(0.2094)	(0.5127)
SIZE	2.3034***	2.2110***	2.1722***
	(0.0879)	(0.0875)	(0.2243)
AGE	0.6510***	0.0585	0.8258***
	(0.0150)	(0.0366)	(0.0344)
DUAL	-0.3504**	-0.4771***	-0.3965
	(0.1673)	(0.1640)	(0.2947)
AUDIT	-1.7398***	-1.8598***	-1.7072**
	(0.3766)	(0.3685)	(0.8079)
DCL	0.0286	0.0376**	0.0268
	(0.0192)	(0.0189)	(0.0259)
year fe	NO	YES	YES
firm fe	NO	NO	YES
N	40219	40219	40219
r2_w	0.217	0.249	0.249

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

Endogeneity testing

Instrumental variable method

Referencing previous research, we use the average OI level of other firms of the same size in the same year (Han et al., 2024) and the number of patent ownership litigation cases resolved in the province where the firm is located in the same year as instrumental variables (IVs) for firms' OI. This approach addresses endogeneity issues as these two variables satisfy the relevance and exogeneity assumptions of IVs. The specific justification is described below.

We categorize all listed companies into deciles by size and calculate the average OI level (Avgopen_innov) for firms in each group, excluding the firm itself, using this average as an IV for OI level. First, the OI level among other firms of the same scale does not directly influence firms' engagement in CE practices, satisfying the exogeneity assumption. Additionally, a firm's OI level is influenced by those of similar-sized firms, satisfying the relevance assumption, meeting IV relevance and exogeneity requirements.

We obtain the number of patent ownership disputes resolved in each province from the Peking University Law Database and use the logarithm of this number plus one (Suit) as an IV for OI at the provincial level. According to the paradox of openness (Laursen & Salter, 2014), managers engage firms in OI by collaborating with a wide range of external actors while simultaneously striving to protect their proprietary knowledge from being copied by competitors. The number of patent ownership disputes in a firm's province is an indicator of the strength of local patent protection (Rudy & Black, 2015), satisfying the relevance assumption. Exogeneity is reflected in the fact that provincial-level patent litigation cases do not directly influence a firm's engagement in CE practices.

This study employs two-stage least squares (2SLS) and generalized method of moments (GMM) estimation for IV regression. The results in the first and second stages of the 2SLS regression are respectively presented in Columns (1) and (2) of Table 3, and the GMM estimation results are presented in Column (3).

The results of the IV test show that the p-value of the LM statistic is 0.0000, rejecting the null hypothesis of IV underidentification. The Wald F statistic is 100.669, far exceeding the 10 % critical threshold of 19.93, indicating no weak IV problem. The p-value of the Sargan statistic is 0.1526, supporting the null hypothesis that all IVs are exogenous and confirming no overidentification issues with the IVs.

In Column (1) of Table 3, the IVs Avgopen_innov and Suit are significant at the 0.01 level, with positive coefficients, satisfying the relevance assumption for the IVs. In Column (2) of Table 3, the explanatory variable is positively significant at the 0.01 level, indicating that after addressing endogeneity issues, the effect of firms' OI on CE practices remains significantly positive, with the coefficient notably increased. The GMM estimation results in Column (3) also support this conclusion.

Table 3
Testing results for endogeneity.

Variables	(1) Open_innov	(2) CEP	(3) CEP	(4) CEP	(5) CEP	(6) CEP
Avgopen_innov	0.1187***					
	(0.0085)					
Suit	0.0106***					
	(0.0039)					
Open_innov		14.1575***	14.1575***			
		(1.3913)	(1.3908)			
Treat_post				2.3807***	2.7724***	2.5233***
				(0.4450)	(0.2016)	(0.2294)
control_var	YES	YES	YES	YES	YES	YES
year fe	YES	YES	YES	YES	YES	YES
firm fe	YES	YES	YES	YES	YES	YES
N	40219	40219	40219	40219	34219	23156
r2_w	.	.	.	0.249	0.244	0.258

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

Difference-in-differences

A firm's OI activities may promote CE practices, whereas its CE practices might encourage OI, indicating a potential bidirectional causality issue. Therefore, this study next investigates the causal relationship between the two by treating firms' OI activities as a quasi-natural experiment. Since the timing of OI varies across firms, we apply a staggered difference-in-differences (DID) model. Referencing previous research (Al Abri et al., 2017), this study identifies the first year in which a firm continuously engaged in OI for at least three years as the point of occurrence for the quasi-natural experiment.

The DID model established in this study is as follows:

$$CEWF_{it} = \beta_0 + \beta_1 Treat_i \times Post_{it} + \sum \beta_n ContVars_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (5)$$

As shown in Column (4) of Table 3, firms' OI adoption significantly enhances their CE practices. We also conduct parallel trends and dynamic effects tests using the DID model.

The results in Fig. 2 demonstrate that the interaction terms are not statistically significant prior to OI implementation, indicating no notable differences between the treatment and control groups, validating the parallel trends assumption. However, after the initiation of OI, the interaction coefficients become significantly positive and exhibit an upward trend. This suggests that OI promotes corporate CE practices and the effect persists over time.

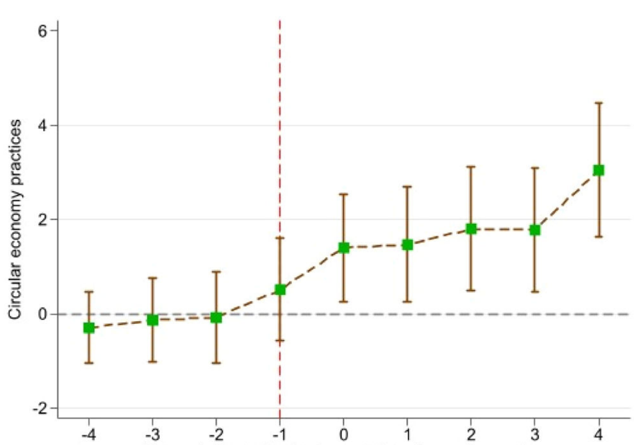

Fig. 2. Parallel trend test.

Propensity score matching

To ensure that the characteristics of firms in the treatment and control groups are similar, we employ propensity score matching (PSM) to pair treatment group samples with the most comparable control group samples. This approach can mitigate the problem of sample selection bias.

Fig. 3 illustrates the results of the PSM, revealing that significant differences between certain variables were evident in the control and treatment groups prior to matching. However, after matching, no significant differences in any variables are apparent between the matched control and treatment groups.

We re-estimate the DID model using the matched samples, presenting the results in Column (5) of Table 3. The findings from the PSM-DID analysis support the baseline conclusions of this study.

Given that PSM matches samples across different years, it is possible that control and treatment group samples from significantly different years could be matched. To address this, we applied a period-by-period matching approach, pairing treatment and control group firms from the same year, using the year before the treatment firm's policy intervention as the baseline. This approach improves comparability by controlling for macroeconomic fluctuations that could otherwise confound the results. The results shown in Column (6) of Table 3 also support our baseline conclusions.

Robustness tests

We next replace the core explanatory variable and exclude samples from certain industries to test the robustness of the baseline regression. Specifically, we change the measure of OI from the logarithm of one plus the number of OIs (Open_innov) to the proportion of OI patents to total

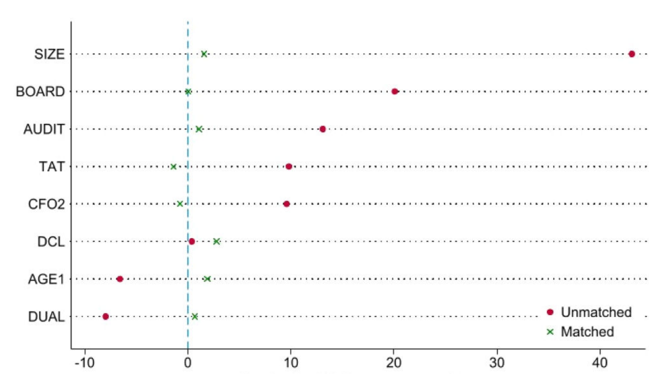

Fig. 3. Matching effect.

patents held by the listed company (Open_innov_ratio). The results of this estimation are shown in Column (1) of Table 4. Furthermore, since collaborative innovation typically occurs within a single firm, we exclude this type of OI and focus only on intracompany and intercompany OIs (Open_innov1). The results of this estimation are presented in Column (2) of Table 4.

Additionally, considering that the impact of OI on corporate CE practices may have a lag effect, we use lagged terms as the core explanatory variable. The estimation results are presented in Column (3) of Table 4. Moreover, since some industries are highly related to CE and could affect the robustness of the results, we exclude data from ecological protection and environmental management and waste resource recycling sectors, presenting the results in Column (4) of Table 4. All robustness test results show that the coefficient of OI remains positive and significant at the 1 % level, demonstrating the validity of the benchmark findings and confirming Hypothesis 1.

Mechanism analysis

Based on Hypotheses 2a–2c, this study employs a two-step method to examine whether commercial credit availability, GKRs, and information exchange mediate the impact of OI on corporate CE practices (Wei et al., 2024). The regression results are presented in Table 5.

Column (1) of Table 5 shows that OI significantly enhances commercial credit access, supporting Hypothesis 2a. Column (2) of Table 5 indicates that OI strengthens green knowledge reserve, confirming Hypothesis 2b. Columns (3) and (4) of Table 5 demonstrate that OI significantly improves information exchange, providing evidence for Hypothesis 2c. Additionally, Column (5) of Table 5 reveals that CE policies significantly influence the relationship between OI and corporate CE practices, supporting Hypothesis 3. All effects are statistically significant at the 1 % level. In Fig. 4, both lines have positive slopes, validating Hypothesis 1, and the slope of the line for companies implementing CE policies is greater than that for those not implementing such policies, supporting Hypothesis 3.

Heterogeneity tests

Collaboration heterogeneity test

OI in companies involves crossing boundaries between different entities (Caccamo et al., 2023). Based on our previous classification of OI types among listed companies, we examine the impact of different types of OI on corporate practices in the CE.

The results in Table 6 show that the coefficients for different types of OI are all positive and statistically significant at the 1 % level. Notably, intercompany OI has the largest coefficient among them.

Table 4
Robustness checks results.

Variables	(1) CEP	(2) CEP	(3) CEP	(4) CEP
Open_innov_ratio	2.1755*** (0.2583)			
Open_innov1		0.9307*** (0.0698)		
Open_innov_lag1			0.9863*** (0.0919)	
Open_innov				1.0325*** (0.0758)
control_var	YES	YES	YES	YES
year fe	YES	YES	YES	YES
firm fe	YES	YES	YES	YES
N	40219	40219	31788	39917
r2_w	0.247	0.249	0.248	0.247

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

Region heterogeneity test

China is a vast country, with significant development disparities across different regions, particularly between eastern and midwestern regions. To assess the impact of OI on the CE practices more accurately, we divide the sample into companies from eastern and midwestern regions, introducing a variable for industrialization level (IL) differences, measured by the ratio of industrial added value to employment.

Fig. 5 illustrates the industrialization differences between eastern and midwestern regions. The eastern region, marked by the red line, clearly shows a higher IL compared with the midwestern region.

Table 7 presents the numerical results of the regional heterogeneity analysis. Columns (1) and (2) of Table 7 report the baseline regression model results for firms in eastern and midwestern regions, respectively. The findings indicate that the coefficients for OI are positive and statistically significant at the 1 % level, with a larger effect observed for firms in the eastern region.

Columns (3) and (4) of Table 7 incorporate CE policy (policy) and the interaction term Open_innov × policy into the baseline regression model, followed by subgroup regressions for firms in eastern and midwestern regions. The results reveal that while the coefficient for OI remains positive and significant at the 1 % level, the interaction term between policy and OI is only positive and significant at the 1 % level in the eastern region.

Columns (5) and (6) of Table 7 further extend the regression model by adding the triple interaction term Open_innov × policy × IL, along with the interaction terms Open_innov × IL and policy × IL. The results demonstrate that while the coefficients for OI remain significantly positive, the triple interaction term is only significantly positive in the eastern region, indicating that the moderating effect of CE policy is more pronounced in areas with higher industrialization levels.

Fig. 6 visually illustrates this conclusion. The line representing higher industrialization levels and CE policy implementation has the steepest slope, demonstrating that the positive impact of OI on CE practices is strongest under these conditions.

Discussion

Our findings highlight the strong influence of OI on advancing CE practices. This aligns with the conclusions of Leonidou et al. (2024), who emphasized the significance of multinational corporate innovation partnerships and Jesus and Jugend (2023), who found that stakeholder interactions and collaborations enhance knowledge dissemination and promote cooperative innovations that are beneficial to CE.

Our results also demonstrate that OI strengthens trust across the supply chain, improving access to trade credit and supporting CE practices. This is consistent with the DSM case study by Kennedy et al. (2017). The RBV perspective indicates that access to commercial credit represents a valuable and rare financial resource that enhances a firm's competitive advantages in implementing CE practices. Additionally, our findings parallel the study's emphasis on "technology scouting" as a critical step before launching circular projects, reinforcing our results confirming that OI expands GKRs by enabling firms to collaborate with universities, research institutions, and industry partners. This enables companies to acquire green patents or obtain patent licenses, thereby strengthening GKRs (Asna Ashari et al., 2023; Kwon et al., 2023; Zhang et al., 2023).

We also find that CE policies positively moderate the relationship between OI and corporate engagement in CE practices, particularly in regions with higher industrialization levels. This aligns with Cassetta et al. (2023), who argued that government incentives and regulatory frameworks encourage product and process innovations through external collaborations, further validating the moderating effects observed in our study. CE policies establish a more favorable environment for CE adoption through mechanisms such as subsidies, tax

Table 5
Mechanism analysis results.

Variables	(1) CTC	(2) GKA	(3) IEL Refered	(4) ACV	(5) CEP
Open_innov	0.0023*** (0.0008)	0.1856*** (0.0046)	0.1786*** (0.0073)	0.0100*** (0.0017)	0.8538*** (0.0852)
Policy					2.1022*** (0.3447)
Open_innov × Policy					0.6905*** (0.1399)
control_var	YES	YES	YES	YES	YES
year fe	YES	YES	YES	YES	YES
firm fe	YES	YES	YES	YES	YES
N	40219	40219	40219	40219	40219
r2_w	0.0689	0.304	0.547	0.275	0.251

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

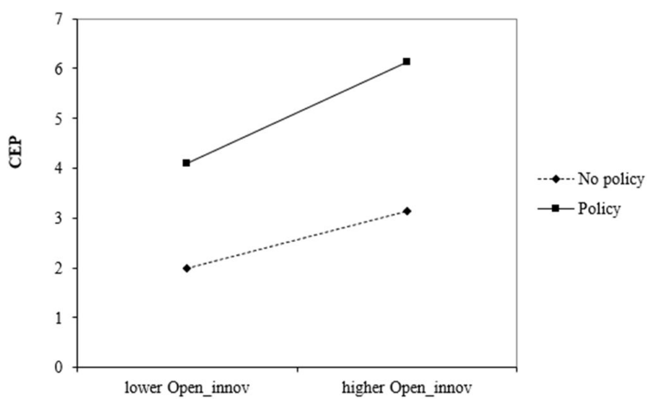

Fig. 4. Effect of Circular economy policy on circular economy practices.

Table 6
Collaboration heterogeneity test results.

Variables	(1) CEP	(2) CEP	(3) CEP
Open_innov_bet_comp	1.8185*** (0.1616)		
Open_innov_in_comp		0.9729*** (0.1006)	
Open_innov_with_comp			0.9314*** (0.1112)
control_var	YES	YES	YES
year fe	YES	YES	YES
firm fe	YES	YES	YES
N	40219	40219	40219
r2_w	0.248	0.248	0.247

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

incentives, and regulatory frameworks that promote innovation in resource recycling technologies (Hartley et al., 2023; Puglia et al., 2024).

Finally, our heterogeneity analysis reveals that CE policies have a significant moderating effect on companies in the eastern region, whereas this effect is insignificant in the midwestern region. This unexpected finding implies potential regional disparities in the effectiveness of CE policy implementation. One possible explanation is that firms in the midwestern region may grapple with greater resource constraints or lack the necessary infrastructure to fully leverage the benefits of OI for CE practices (Zhou et al., 2024). Additionally, differences in local government enforcement and support mechanisms may contribute to the varying impact of CE policies (Puglia et al., 2024). Further research is needed to explore these regional variations and their implications for CE policy design and corporate strategy.

Conclusion

Key findings

This study examines the impact of OI on corporate CE practices using patent data and annual reports from companies listed on China's A-share and STAR markets from 2003 to 2022. We employ TWFE, mediating effect, and moderating effect models for empirical regression, contributing to the literature on the mechanisms through which OI influences the CE. Our findings indicate that OI has a significant influence on promoting corporate CE practices, and this conclusion is validated using various endogeneity and robustness tests. Specifically, OI enhances corporate engagement in CE practices by improving trade credit availability, expanding GKRs, and strengthening information exchange. Moreover, our results reveal that CE policies positively moderate the relationship between OI and corporate CE practices. Additionally, the moderating effect is stronger in regions with higher industrialization levels, indicating that industrialization is crucial condition effective implementation of government CE policies.

Contributions and implications

Our study contributes to the literature by providing a deeper understanding of how OI functions as a key driver of CE practices. We establish a theoretical framework that identifies commercial credit acquisition, GKRs, and information exchange as the three critical mechanisms through which OI facilitates CE adoption. Using an extensive panel dataset of Chinese listed firms from 2003 to 2022, our empirical analysis provides robust evidence validating these mechanisms, offering new insights into the intricate connection between OI and sustainable business transformation. Furthermore, our results demonstrate that CE policies positively moderate this relationship, and this effect is more pronounced in regions with higher industrialization levels. This highlights the significance of policy design for fostering a supportive institutional environment for sustainable innovation, while also revealing potential regional disparities in policy effectiveness.

Based on these findings, we recommend that the government promote OI by providing financial support and incentives for cross-sector collaboration, which will help advance CE practices (Belderbos et al., 2014). Additionally, considering the regional differences in industrial development, differentiated policies tailored to specific regions can further enhance the effectiveness of CE initiatives, ensuring more balanced progress across the nation (Puglia et al., 2024).

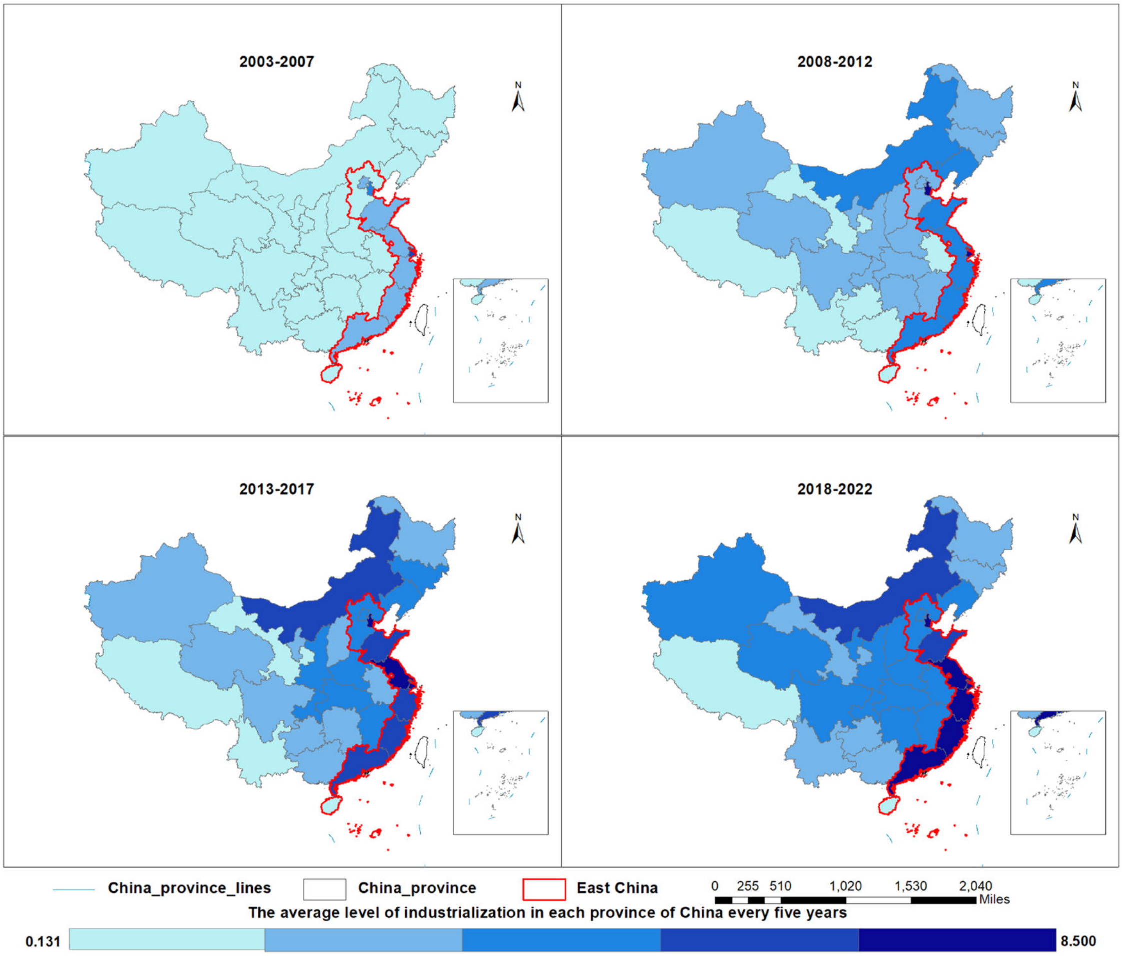

Fig. 5. Map of the difference in the level of industrialization between the eastern and midwestern regions.

Table 7
Region heterogeneity test results.

Variables	(1) CEP Eastern regions	(2) CEP Midwestern regions	(3) CEP Eastern regions	(4) CEP Midwestern regions	(5) CEP Eastern regions	(6) CEP Midwestern regions
Open_innov	1.1946***	0.6756***	0.9904***	0.5773***	0.6842***	0.6440*
	(0.0890)	(0.1551)	(0.0955)	(0.1840)	(0.1106)	(0.3324)
Policy			1.8926***	-0.7720	1.7286***	1.3296
			(0.3663)	(1.0734)	(0.3781)	(1.1790)
Open_innov × Policy			0.8671***	0.2966	0.4824***	0.6689
			(0.1587)	(0.2922)	(0.1718)	(0.7048)
Open_innov × Policy × IL					0.2897***	0.3359
					(0.0887)	(0.3179)
Open_innov × IL					0.1795***	0.1567
					(0.0460)	(0.1528)
Policy × IL					0.2823**	1.1529***
					(0.1319)	(0.2710)
control_var	YES	YES	YES	YES	YES	YES
year fe	YES	YES	YES	YES	YES	YES
firm fe	YES	YES	YES	YES	YES	YES
N	27960	12259	27960	12259	27960	12259
r2_w	0.227	0.297	0.229	0.297	0.230	0.299

Note. The value of t-statistics reported in parentheses; ***, **, * indicate that the bilateral test is significant at 1 %, 5 %, and 10 %, respectively.

Limitations and future research directions

Companies' OI should be understood as a broad collaborative process involving partnerships with universities, research institutions, communities, and the general public. However, the indicators used in this study do not fully capture all forms of collaboration, as OI is primarily measured using patent data. This approach may overlook other important OI dimensions such as industry–university partnerships, community-driven innovation, and knowledge sharing platforms. Additionally, this study focuses on Chinese listed companies, which may not fully represent the characteristics of SMEs or firms in other economies. Since SMEs often exhibit different innovation patterns and

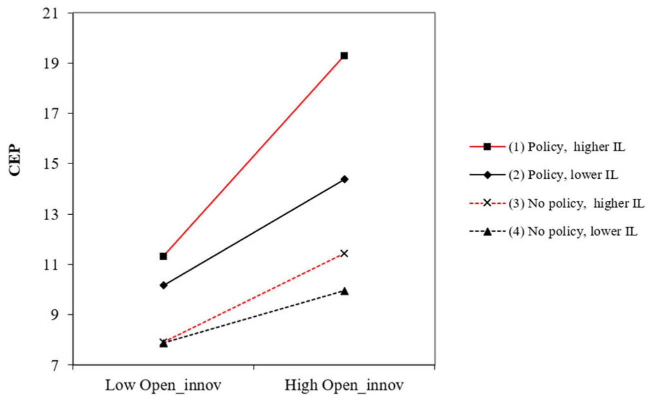

Fig. 6. Effect of Circular economy policy and industrialization levels on circular economy practices.

resource constraints, the impact of OI on CE practices observed in this study may change when SMEs are included in the sample.

Future research could explore additional types of OI beyond patent-based indicators, incorporating measures such as coauthored publications, joint research projects, and technology licensing agreements. Additionally, future studies could investigate the characteristics of firms engaged in OI collaborations and examine whether geographical distance and industry differences have heterogeneous influence on CE practices. Such research would contribute to a more comprehensive understanding of how OI affects CE practices and provide more accurate insights for future

CRediT authorship contribution statement

Xingmin Yin: Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Yun Jin:** Writing – review & editing, Software, Investigation, Data curation. **Zhou Li:** Writing – review & editing, Validation. **Yulin Liu:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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