Journal of Innovation & Knowledge 10 (2025) 100783

Contents lists available at ScienceDirect

Journal of Innovation & Knowledge

journal homepage: www.elsevier.com/locate/jik

From collaboration to green transformation: How strategic alliances drive green total factor productivity through dynamic capabilities?

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A R T I C L E I N F O

JEL code:
Q55
L14
O33

Keywords:
Strategic alliances
Open innovation
Green total factor productivity
Dynamic capabilities
Green cognition
Standard-setting
Environmental regulation
Circular economy

A B S T R A C T

The escalating environmental crises have led to the emergence of strategic alliances as a pivotal open innovation mechanism driving circular transitions. This study pioneers an investigation by systematically examining how strategic alliances enhance the green total factor productivity (GTFP) of firms. Utilizing a balanced panel dataset of Chinese industrial listed firms (2012–2022), the results confirm that participation in strategic alliances significantly promotes firms' GTFP. Based on the dynamic capabilities theory, the mediation analysis reveals that enhancing the green cognition of firms' senior management and local (rather than national) standard-setting levels serves as a critical mechanism through which alliances elevate GTFP. Consistent with the Porter hypothesis, the moderation analysis identifies stringent environmental regulation as catalytic institutional forces amplifying alliance effectiveness in improving GTFP. Furthermore, heterogeneity analyses across regions and industries delineate boundary conditions, emphasizing the significant impact of external environments and sectoral conditions on green transformation, moving beyond universal claims of "whether alliances matter" towards exploring "where and why they matter most." This study contributes to the theoretical research on strategic alliances and the circular economy. Moreover, it offers valuable insights for firms' decision makers to leverage alliance networks for innovating circular business models and for policymakers to optimize environmental governance frameworks for circular transition.

Introduction

The existence of external resources and intercorporate connections has long been identified as a source of competitive advantage for firms (Dyer & Singh, 1998). With the popularity of open innovation, strategic alliances—defined as voluntary collaborative arrangements for resource exchange and joint objective attainment (Dacin et al., 2007; Gulati, 1998)—have enabled firms to overcome resource constraints while pursuing technological advancements (Shukla et al., 2020). Compared with conventional collaborative relationships, strategic alliances emphasize resource complementarity and synergistic effects (Das & Teng, 2000).

The increasing uncertainty and complexity of the global business environment have led many firms to establish strategic alliances within a diverse network of stakeholders to facilitate the exchange of information, resources, capabilities, technologies, and knowledge. Extensive studies recognize the importance of strategic alliances in enhancing firms' performance, including enabling firms to reduce risks and costs, integrate complementary resources and capabilities, overcome technological constraints, access new markets and product domains, and achieve economies of scale and scope (Bai et al., 2024; Das & Teng, 2000; Niesten & Jolink, 2020; Oh et al., 2024). However, despite these multifaceted benefits, the alliance literature predominantly prioritizes economic value maximization as the ultimate goal (Lavie, 2007; Madhok & Tallman, 1998; Nickerson, Silverman, & Zenger, 2007), neglecting performance trade-offs. Empirical evidence suggests U-shaped relationships between alliance intensity and innovation performance (Wassmer, 2010), with deficient learning and knowledge transfer capabilities exacerbating resource misallocation risks (Kale & Singh, 2007). These contradictions necessitate a paradigm shift in evaluating alliance outcomes through sustainability-oriented lenses.

Given China's dual challenge of sustaining economic growth while addressing environmental degradation, the imperative to achieve a circular economy has become increasingly urgent (Li et al., 2018; Shi & Xu, 2018; Tu, 2024; Zhang et al., 2021). As the world's largest carbon emitter, China accounted for approximately 34 % of global carbon

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https://doi.org/10.1016/j.jik.2025.100783
Received 26 March 2025; Accepted 8 August 2025
Available online 27 August 2025

emissions in 2023, surpassing the total emissions of developed economies (International Energy Agency, 2023). To reduce climate change and carbon emissions, the Chinese government has implemented a series of proactive measures, including setting carbon peak and carbon neutrality (Dual Carbon) targets, optimizing industrial and energy structures, and promoting the development of clean energy (Lv et al., 2023). Owing to the environmental challenges of emissions reduction, firms—especially industrial firms, as the primary sources of pollution—face mounting pressure to align with government regulations and policies. Importantly, as market demands for environmental accountability intensify, pursuing green economic growth has shifted from a discretionary option to a strategic necessity (Li et al., 2016). This paradigm shift fundamentally underscores why enhancing firms' green practices is crucial not only for China's green economic transition but also for strengthening global environmental governance (Dong et al., 2022). In this context, green total factor productivity (GTFP), which integrates environmental externalities into traditional productivity assessments, has emerged as a strategic prerequisite for achieving circular economy transitions. This green production model not only enhances production efficiency and competitiveness but also aligns with societal expectations for sustainable corporate operation and social responsibility (Wang et al., 2022; Yan et al., 2024). However, achieving improvements in GTFP necessitates cross-domain knowledge integration and specialized competencies (Ardito et al., 2019a, 2019b), which often exceed individual firms' endowments. Thus, strategic alliances offer a vital channel for acquiring environmental knowledge and complementary green resources (Das & Teng, 2000; Etzion, 2007); however, the mechanisms translating alliance resources into improvements in GTFP remain underexplored, leaving critical theoretical and practical gaps in understanding sustainable transitions.

The resource-based view (RBV) (Wernerfelt, 1984) posits that strategic alliances facilitate the bidirectional or multidirectional flow of strategic resources among firms (Das & Teng, 2000), including the sharing of valuable environmental information and opportunities. This allows firms to replicate successful environmental strategies and improve their GTFP, increasing their competitive advantage while benefiting the environment (Etzion, 2007; Reinhardt, 1998). However, the RBV's static conceptualization of resources inadequately explains how firms dynamically reconfigure alliance-derived assets to meet evolving environmental demands (Khan et al., 2021; Moghaddam et al., 2016; Priem & Butler, 2001). The dynamic capabilities theory bridges this gap by emphasizing that firms' capacities to sense environmental opportunities, seize them via resource reconfiguration, and transform internal processes into sustainable advantages (Eisenhardt & Martin, 2000; Teece, 2007). Although the dynamic capabilities theory highlights the significance of environmental change in influencing firms' adaptive processes and resource orchestration (Aragón-Correa & Sharma, 2003; Oliver & Holzinger, 2008; Teece et al., 1997), it provides limited insight into how formal institutional pressures interact with micro-level alliance strategies to collectively shape environmental performance outcomes. The institutional theory (Li & Abiad, 1990) complements this framework by positing that environmental regulation reconfigures the strategic value of alliances: stringent policies amplify the marginal returns of alliance activities by incentivizing firms to prioritize green resource sharing (e.g., clean technology transfer), or, conversely, suppress collaboration efficiency under regulatory ambiguity. Furthermore, while studies recognize the green cognition of senior management and standardization practices as firms' important capabilities, their mediating roles in converting alliance resources into systemic green transformations require theoretical elaboration. These theoretical lacunae call for an integrative framework that unites resource complementarity, dynamic adaptation, and institutional contingencies.

Guided by this theoretical synthesis, this study addresses three research questions: (1) Do firms' participation in strategic alliances promote GTFP? (2) Do firms' green cognition of senior management and standard-setting level play mediating roles in the relationship between strategic alliances and GTFP? (3) Does environmental regulation moderate the relationship between strategic alliances and GTFP? By integrating the RBV, dynamic capabilities theory, and institutional theory, this study empirically investigates the impact of strategic alliance participation on the GTFP of industrial-listed firms in mainland China between 2012 and 2022. We propose a dual-path mediation model: alliances foster GTFP not only through senior management's enhanced environmental sensemaking (sensing capability) but also through codifying green practices via standardization (seizing and reconfiguring capability). Additionally, we explore the impact of regulatory pressure and contextual contingencies on the alliance–GTFP relationship.

This study contributes to three domains. First, theoretically, it extends alliance performance research from profit-centric paradigms to sustainability outcomes. This aligns with the stakeholder theory's emphasis on multidimensional value creation (Freeman, 1984) while resolving the RBV's static limitations through dynamic capability mechanisms and addressing the institutional theory's macro–micro disconnect. Second, methodologically, this study integrates the super slack-based measure (super-SBM) model with non-radial efficiency measurement and the global Malmquist–Luenberger productivity index (GML index) to estimate the GTFP of the observations. Compared with the traditional radial measurement in directional distance functions and the Malmquist–Luenberger index (Debbarma et al., 2022), this method offers a more accurate and comprehensive assessment of environmental and economic performance changes, which is a vital distinction for testing dynamic capability theorization. Finally, practically, based on our findings, this study proposes targeted policy recommendations and managerial insights, which are not only practical for firms to promote circular business model innovation but also provide valuable references for the circular economy, sustainable development, and environmental well-being in other developing economies.

The remaining study is organized as follows: Section 2 provides the theoretical background and hypotheses. Section 3 presents the methodology and data. Section 4 demonstrates the model results and analysis of the results, followed by the discussion in Section 5. Section 6 provides the conclusions. Sections 7 and 8 detail the policy and managerial implications and the limitations of the study, respectively.

Theory and hypotheses

Theoretical background

Strategic alliances, as an important organizational form for firms, refer to the strategic partnerships established between firms and their stakeholders. Through agreements, the entities in the alliance form a collaborative organization characterized by complementary advantages, shared risks, and bidirectional or multidirectional flow of production factors (Lin & Darnall, 2010). As the establishment and participation in strategic alliances have become increasingly common, substantial literature has focused on strategic alliances and their economic, organizational, and environmental effects.

First, strategic alliances are means for co-creating economic value that individual firms cannot achieve on their own (Dyer & Singh, 1998; Lavie, 2007). Through collaboration with recognized industry leaders, a firm leverages its partner's market visibility and reputation to enhance its own market position, market value, and customer reach (Arino et al., 2008; Jiang et al., 2010; Li, 2013). In China, such alliances often enable local manufacturers to secure preferential access to distribution channels and government procurement programs under initiatives like "Made in China 2025" (Zhang & Zhang, 2024). These collaborations reduce transaction costs through shared R&D investments and risk pooling under volatile market conditions (Lazzarini, 2007; Vanhaverbeke & Noorderhaven, 2001), ultimately augmenting financial performance (Parmigiani & Rivera-Santos, 2011).

Second, beyond immediate payoffs, strategic alliances drive firms' enduring competitive advantages by fostering dynamic capabilities

(Han et al., 2018; Helfat & Raubitschek, 2018; Teece et al., 1997). On the one hand, alliances bridge internal R&D gaps (Li, 2013; Owen & Yawson, 2015) and enhance innovation prowess by accessing external technologies (Kavusan et al., 2016; Li et al., 2008; Radicic et al., 2020; Scaringella & Radziwon, 2018; Subramanian et al., 2018), particularly critical in sectors such as traditional manufacturing where independent innovation is time-intensive (Oh et al., 2024). On the other hand, as strategic alliances establish a reciprocal relationship, partners are more likely to trust each other and share tacit and unprotected knowledge (Diestre, 2018; Oxley & Wada, 2009; Sampson, 2007). Additionally, frequent interactions between alliance partners provide firms with more learning opportunities (Faems et al., 2012), gradually enhancing their ability to assimilate external insights (Baum et al., 2000). These dynamic capabilities are further shaped by stakeholder interactions—ongoing dialogues with regulators, non-governmental organizations, suppliers, and customers help senior management develop green cognition, which guides the reconfiguration of routines and investment toward circular innovation (Mitchell et al., 1997).

Finally, as environmental challenges intensify, strategic alliances enable firms to address sustainability imperatives beyond standalone capabilities (Bai et al., 2024). Under China's increasingly stringent environmental regulation, such as the Ecological Civilization System, firms strategically select partners with complementary environmental technologies or certifications—not only to mitigate environmental risks but also to demonstrate compliance with evolving regulations and to build institutional legitimacy. In this context, alliances often participate in alliance-driven standard-setting initiatives, enabling firms to both influence emerging norms and adapt their internal processes accordingly (Blind & Thumm, 2004). By aligning alliance objectives with government mandates and consumer expectations for green products, firms operationalize resource heterogeneity (RBV) and institutional theory insights in pursuit of scalable green outcomes.

Strategic alliances and GTFP

According to the RBV (Wernerfelt, 1984), firms agglomerate various resources, and significant variations exist in their competitive advantages owing to the heterogeneity in their endowments of both tangible and intangible assets (Barney & Clark, 2007). In China, environmental protection has become a national strategic priority. Simultaneously, the government has called for placing industrial growth "firmly at a prominent position" while accelerating the transition to green, low-carbon development. Coordinating these dual objectives poses a fundamental challenge for both policy design and industrial practice. In this context, strategic alliances have emerged as a key mechanism for overcoming resource and technological constraints; such partnerships can reinforce the stability and competitiveness of China's industrial sector even as it advances toward more sustainable, carbon-conscious operations. The RBV emphasizes the necessity of establishing external networks through which firms can access multiple complementary resources, including financial, knowledge, and technological assets (Barney & Clark, 2007). Under China's institutional regime, with its blend of market-based instruments (e.g., emissions trading scheme (ETS) subsidies) and government-led planning (Zhang & Zhang, 2024), alliances enable firms to pool resources in ways that substantively improve GTFP.

First, Das and Teng (2000) are the first to apply the RBV to investigate strategic alliances, emphasizing that the essence of strategic alliances lies in the integration of firms' resources. The antecedent of this resource integration is that strategic alliances promote communication and interaction between firms and horizontal bidirectional flow of production factors (Gulati, 1995). Through strategic collaboration, firms gain access to complementary green production inputs from their partners, such as environmental technologies, circular processes, and advanced low-caron equipment, in addition to their financial, technological, and market resources (Ireland et al., 2002; Niesten & Jolink, 2015). By co-investing in shared facilities and jointly exploiting patented processes, alliance partners gain economies of scale and scope. In China, this mechanism is particularly significant owing to disparities in green capabilities among firms (Guo et al., 2020). For instance, Volkswagen and the Chinese power-battery supplier GOTION HIGH-TECH have entered into a battery production cooperation through an equity transaction in compliance with China's circular economy regulations. This collaboration allowed both firms to share R&D expenditures and leverage proprietary manufacturing techniques, securing Volkswagen's battery supply while bolstering GOTION's technological capabilities and market penetration. Such resource-sharing arrangements raise output levels without proportionally increasing input usage, enhancing GTFP.

Second, strategic alliances foster the accumulation of knowledge and capabilities that create substantial value (Dyer, 1997). By facilitating frequent interactions and blurring organizational boundaries, alliances enable the transfer of tacit knowledge (Anand & Khanna, 2000; Diestre, 2018; Simonin, 1997; Spralls et al., 2011), such as advanced energy-efficient production protocols or emission reduction techniques. Geographical proximity among partners, as exemplified by the solar manufacturing cluster in Jiangsu Province, China (e.g., Trina Solar and Jinko Solar), accelerates localized sustainability learning and reduces trial-and-error costs (Ardito et al., 2019b). Collaboration with technologically diverse partners mitigates the risks inherent in green innovation (Ardito et al., 2019a). This is because environmental technologies, characterized by high technological breadth, are more easily understood and adopted across industries, creating abundant opportunities for knowledge recombination and subsequent technological advancement (Ardito et al., 2019a). Taking Chinese automotive firm BYD as an example, the firm entered into a 50/50 joint venture with Toyota in 2020 (BYD Toyota EV Technology Co., Ltd.) to co-develop electric vehicles and batteries. By leveraging BYD's expertise in cost-efficient blade battery (LFP) technology and Toyota's hybrid system integration capabilities, this long-term institutional arrangement accelerated the deployment of scalable solutions. This cross-industry synergy is epitomized by their co-created bZ3 sedan, which integrates BYD's battery innovations with Toyota's safety and quality management systems, achieving a 616-km range on a single charge (Toyota Motor China, 2023) while reducing production costs through localized supply chains (Financial Times, 2023). More importantly, the joint venture has established co-located R&D centers in two Chinese cities, where engineers from both firms engage in daily collaboration and collective problem-solving. Such sustained, reciprocal knowledge exchange embodies the "patient capital" paradigm (Ardito et al., 2019b), transforming one-off resource transfers into enduring organizational capabilities and, in turn, driving systemic innovation that enhances GTFP (Faucheux & Nicolaï, 2011).

Furthermore, strategic alliances reinforce trust between firms and their upstream and downstream business partners (Cheng et al., 2008), which promotes the flow of information (Chaudhuri et al., 2018) and alleviates asymmetry across the supply chain (Gulati, 1995). In China's policy milieu, where government procurement criteria and emerging ESG ratings increasingly reward green supply chain practices (Zhang & Zhang, 2024), such alliances provide a structured forum for harmonizing environmental objectives among all participants. This alignment not only enhances logistical coordination and operational efficiency (Kong et al., 2020) but also lowers transaction and overhead costs, improving the overall efficiency of resource utilization (Du et al., 2018; Fontoura & Coelho, 2022; Mondal & Giri, 2022). Crucially, the trust-based governance and transparent data-sharing mechanisms that alliances establish create a durable foundation for joint environmental management, enabling partners to exchange best practices in waste reduction and energy conservation. Over time, these collaborative frameworks drive significant reductions in waste streams and optimize material throughput, yielding measurable gains in GTFP. A significant example is the 2022 joint initiative by Alibaba's Cainiao logistics platform and multiple packaging suppliers to develop recyclable green packaging solutions for firms such as Nestlé. Through this alliance, design specifications, recyclable materials, and logistics processes were standardized across partners, reducing waste and enhancing the material reuse rates. Thus, we propose the following hypothesis:

H1. Firms' participation in strategic alliances positively affects GTFP.

Mediating effect of green cognition of senior management

The synergistic integration of the RBV and dynamic capabilities theory offers a more nuanced understanding of how strategic alliances contribute to green transformation and improvements in GTFP. Although the RBV emphasizes the importance of acquiring and leveraging valuable, rare, inimitable, and non-substitutable resources, it often assumes that these resources are statically deployed within firms (Khan et al., 2021; Moghaddam et al., 2016; Priem & Butler, 2001). However, in fast-changing institutional environments marked by environmental policy shifts and market volatility, merely possessing resources is insufficient. The dynamic capabilities theory complements the RBV by highlighting firms' capacity to sense external opportunities, seize them through strategic resource reconfiguration, and transform internal operations accordingly (Eisenhardt & Martin, 2000; Teece, 2007). In the context of strategic alliances, this synergy manifests in firms that dynamically mobilize and reconfigure alliance-derived resources in response to external environmental pressures, creating an adaptive trajectory of green transformation.

Within this dynamic, the role of senior management becomes particularly critical (Das & He, 2006; McGrath & MacMillan, 1995). According to Eisenhardt and Schoonhoven (1996), senior management acts as the "conceptualizers of alliance strategy." They continually scan diverse stakeholders for environmental signals, ranging from alliance partners and customers to regulatory and non-governmental actors such as central ministries, local environmental bureaus, and industry associations. In China's multilayered governance environment, these actors exert normative and coercive pressures that interact with the green cognition of senior management, shaping organizational behaviors and long-term innovation trajectories (Chen et al., 2006; Li & Zhang, 2023; Tu, 2024). The stakeholder theory clarifies that these external actors provide both normative benchmarks (defining what constitutes "good" environmental performance) and strategic intelligence (emergent market needs and regulatory roadmaps) that managers must sense, interpret, and respond to (Freeman, 1984). By actively monitoring and engaging with diverse stakeholders, firms build the sensing mechanisms described in the dynamic capabilities theory, transforming external signals into actionable knowledge. For example, Everywin Precision, a Chinese electronic components manufacturer, participated in Apple's recycled-materials working groups, enabling its leadership to sense the tightening of global sustainability standards and the commercial premium for low-carbon products. This has prompted the firm to adopt 100 percent recycled aluminum for Mac casings (carbon footprint = 1/40 of primary aluminum) (Apple Inc., 2024) and reposition its alliance resources as strategic green assets.

Then, organizational learning theory describes the parallel processes by which those sensed insights are assimilated into the firm's knowledge base (Argyris & Schön, 1978; Mariotti, 2012). Firms often face challenges in independently acquiring specialized green knowledge owing to institutional barriers such as information asymmetry and agency problems (Zhao et al., 2011). Through alliance-based routines, such as joint R&D workshops, cross-functional learning teams, and shared performance dashboards, managers systematically filter, contextualize, and codify the stakeholder-driven inputs (Darvishmotevali & Altinay, 2022; Gomes-Casseres et al., 2006), enriching firms' internal knowledge repositories (Grant & Baden-Fuller, 2010). A pertinent case is the China Mobile–Huawei partnership to deploy a 5 G dedicated slicing network for State Grid: China Mobile and Huawei translated power sector latency and reliability requirements into new network planning protocols and engineering standards, embedding those green-signal-derived routines into China Mobile's operational documents.

Considering the stakeholder and organizational learning theories as complementary facets of the dynamic "sense" process, we capture how senior management detects, interprets, and internalizes environmental imperatives from their alliance networks. Therefore, based on the above analysis, we propose the following hypothesis:

H2. Green cognition of senior management mediates the relationship between strategic alliances and GTFP.

Mediating effect of standard-setting level

According to Blind and Thumm (2004), standards are rules and normative documents that are approved by authoritative public institutions and apply to products, processes, production methods, packaging, symbols, and other industry-specific regulations. The growth in globalization and technological innovation effectuates the emergence of the development and dissemination of standards as central drivers of firm competitiveness (Blind et al., 2018; Brandi & Souza, 2009). In this respect, a firm's capacity to influence standard setting is widely recognized as a "dynamic capability" that sustains competitive advantage amid evolving external conditions (Leiponen, 2008). This capacity aligns closely with the "seize" and "reconfigure" mechanisms articulated in the dynamic capabilities theory (Teece, 2007), since standards outline industry best practices (Tassey, 2000) and signal preferred technological trajectories (Lerner & Tirole, 2015).

In China's green transformation context, shaped by national directives such as the "Dual Carbon" policy and by regional pilot zone initiatives, firms strengthening their standard-setting posture secure enhanced legitimacy and first-mover advantages in nascent green markets. By anchoring new technologies within formal guidelines, these firms reduce external uncertainty (Aggarwal et al., 2011; Blind et al., 2017), shape collective technological expectations (Lerner & Tirole, 2015), and coordinate the diffusion of novel frameworks across the industry (Baron & Schmidt, 2014; Spulber, 2008). However, given that standard setting entails substantial investment and risk (Jiang et al., 2019), strategic alliances have become the means through which firms assemble the technological, financial, and legitimacy resources required to support these endeavors (Weiss & Cargill, 1992). Hence, alliances operationalize the RBV's focus on heterogeneous resource endowments while illustrating how these resources are reconfigured into binding industry benchmarks, a synergy especially vital in China's rapidly shifting policy environment and fragmented innovation ecosystem (Yu et al., 2019). By collaborating with technology partners, policy entities, and research institutes, alliance members jointly develop technical and normative frameworks, effectively codifying their expertise into industry standards.

In the technological integration dimension, open innovation networks formed through strategic alliances enable firms to "seize" heterogeneous green-technology inputs by leveraging partner screening and absorptive capacity (Jiang et al., 2019). For instance, CATL, a Chinese new-energy firm, collaborated with the State Grid Corporation of China to pilot a sodium–lithium hybrid-storage management standard for fast-charging electric vehicle stations exemplifies this process. Joint R&D efforts yielded a 20 % reduction in per-kilowatt-hour costs and boosted system efficiency to 92 % (SMM, 2025); these outcomes were institutionalized in a nationally endorsed framework guiding China's fast-charging network. By codifying these modular innovations into formal guidelines, CATL enhanced its technological foresight and markedly increased its influence within standard-setting committees (Li et al., 2019). Thus, the resulting standard serves as a "common language" that minimizes duplicated R&D efforts, aligns industry investment, and accelerates the scaling of green technologies, collectively strengthening the GTFP of alliance members.

In the normative negotiation dimension, strategic alliances allow firms to convert legitimacy assets, such as policy expertise and institutional credibility, into substantive rule-making power (Eisenhardt & Schoonhoven, 1996; Parmigiani & Rivera-Santos, 2011). For instance, Goldwind, a Chinese wind-power manufacturer, partnered with the China General Certification Center to establish China's first wind turbine carbon footprint accounting standard, titled Product Carbon Footprint Evaluation Category Rules: Wind Turbine Generator. By harnessing the center's regulatory authority, Goldwind embedded its carbon monitoring methodology into the national standard, which mandates that unit generation emissions remain below 1 % of coal-fired benchmarks (Goldwind Science & Technology Co., Ltd., 2025). This "rule-based dividend" reduced Goldwind's compliance costs and erected certification barriers such as patents, technology licensing, and product certification. Conversely, latecomer firms must prioritize resource allocation and make significant R&D investments to undertake costly technological upgrades and meet these thresholds. Therefore, they often find themselves entrapped in a "compliance catch-up" dilemma, where continuous catch-up pressures consume resources that can otherwise support proactive innovation. Simultaneously, Goldwind can capture additional returns through patent licensing and carbon management service offerings (Lerner & Tirole, 2015). Through this mechanism, standard participant firms entrench their competitive advantage and propagate green innovations across industries, enhancing allocative efficiency and driving economies of scale in China's renewable energy sector.

In sum, the mediating effect of standard-setting level in China's green transformation operates through the dual dynamic capability processes of "seize" and "reconfigure." By transforming distinctive resource endowments such as specialized technological knowledge, institutional ties, and regulatory insights into binding industry frameworks, firms secure valuable and rare competitive advantages. This process enables them to steer the collective technological trajectory of their sectors, driving improvements in GTFP. Accordingly, the following hypothesis is proposed:

H3. Standard-setting level mediates the relationship between strategic alliances and GTFP.

Moderating effect of environmental regulation

Institutional economics theory (Li & Abiad, 1990) posits that institutions resemble the "rules of the game" and influence and constrain organizational behavior (Yang et al., 2012). Environmental regulation is a form of institutional constraint through which governments establish and enforce regulations to guide firms' environmental actions (Blind, 2012). Existing literature reveals three main perspectives regarding the impact of environmental regulation on firms' development.

The first perspective, based on neoclassical economic theory, suggests that environmental regulation may harm firm productivity. The implementation of environmental regulation can disrupt a firm's regular activities to some extent (Ramanathan et al., 2018). This is because external pressures from environmental regulation affect the allocation of production resources within firms, forcing them to allocate more resources to pollution control measures (Gray et al., 2014; Jorgenson & Wilcoxen, 1990). This causes a crowding-out effect, where resources that could otherwise be used for R&D and other improvements are diverted (Albrizio et al., 2017; Lv et al., 2023). Additionally, compliance pressures lead firms to invest in unnecessary non-productive assets, such as purchasing environment-friendly production equipment (Li et al., 2022; Ren et al., 2021). Consequently, environmental regulation can suppress productivity by increasing operational costs (Gary & Shadbegian, 2003). The second perspective supports the Porter hypothesis (Porter & Linde, 1995), which claims that properly designed environmental regulation enhances local economic competitiveness while fostering a greener environment. According to this view, environmental regulation not only encourages firms to adopt cleaner production technologies and processes (Zhang et al., 2020), but also incentivizes innovation in pollution reduction. This, in turn, attracts ongoing government innovation support, fostering green technological advancements and enhancing firm productivity (Johnstone, 2012; Ley et al., 2016; Ren et al., 2019). The third perspective suggests that the impact of environmental regulation on productivity is uncertain, with a non-monotonic or non-significant relationship between the two. They believe that environmental regulation can promote an increase in firms' TFP in the long run (Zhang & Du, 2020); however, such regulation may suppress their original innovation development (Li & Wu, 2017). Additionally, evolutionary economics suggests that firms exhibit diverse characteristics, engendering varying behavioral patterns. Hence, not all environmental regulations have a universally positive impact on firms. This view is supported by empirical studies (Ghosal et al., 2019; Jiang et al., 2018).

However, research on the impact of environmental regulation on firms' GTFP is relatively scarce (Cai et al., 2016; Ren et al., 2019). China's rapid economic expansion, historically driven by investment- and factor-intensive growth, has precipitated severe environmental degradation and stagnating GTFP (Cai & Zhou, 2017). This context positions environmental regulation as a critical institutional lever to recalibrate economic incentives (Yuan & Xie, 2014). Unlike traditional industrial policies that rely on top-down administrative interventions, environmental regulation introduces market-aligned incentives by internalizing ecological costs into firms' decision-making (Zhang et al., 2020). Institutional economics highlights the dual role of regulation: it acts not merely as a constraint but as a catalyst for redefining collaborative value creation. This is a dynamic process that triggers divergent strategic adaptations to institutional pressures (North, 2005; Oliver, 1991), which has been confirmed in China.

In the early regulatory phase, when emissions and energy-intensity targets first emerged, compliance costs were moderate. Firms responded by forming strategic alliances focused on cost sharing and risk mitigation rather than innovation (Lazzarini, 2007; Li & Zhang, 2023; Lv et al., 2023). For example, coal-fired power plants in Shandong Province collaborated to meet SO_2 reduction under the Flue Gas Desulfurization Project, achieving marginal efficiency improvements but no systemic upgrades were made, and overall GTFP gains were negligible (World Bank, 2006). This phase exemplified path-dependent collaborations anchored in static resource complementarity (Leiponen, 2008), where alliances prioritized short-term survival over transformative change, suppressing productivity as resources were diverted to compliance (Albrizio et al., 2017).

As environmental regulation grew more demanding and market-based mechanisms (e.g., carbon trading systems) were introduced, compliance costs escalated and incentives shifted toward value-creating innovation (Porter & Linde, 1995). In this later phase, firms increasingly leveraged strategic alliances for innovation-driven resource pooling (Kanashiro, 2020; Wang & Chen, 2017). For instance, China's home appliance leader Haier began requiring key environmental qualifications—such as ISO 14001 certification and compliance with ROHS and REACH standards—for its suppliers, using these partnerships to co-develop energy-efficient production processes that directly cut carbon emissions. These collaborations transformed alliances from risk-sharing tools into engines of GTFP-enhancing innovation (Testa et al., 2011; Yuan et al., 2021), mirroring China's broader transition from factor-driven to innovation-driven growth.

The moderating role of environmental regulation is inherently contingent, shaped by phased intensity, enforcement credibility, and sectoral adaptability (Lv et al., 2023). Furthermore, China's institutional hybridity—blending state mandates with market mechanisms—underscores environmental regulation as an evolving force that dynamically reconfigures alliance efficacy. By anchoring analysis in China's regulatory experimentation, this study advances a context-sensitive framework for understanding alliance-driven sustainability transitions, where institutional design and strategic adaptation co-evolve to shape GTFP outcomes. Thus, we propose the following hypothesis:

H4. Environmental regulation moderates the relationship between strategic alliances and GTFP.

Based on the above analysis and the hypotheses, Fig. 1 shows the theoretical model established in this study.

Methodology and data

GTFP measurement

This study combines the super-SBM model with the GML index to measure the changes in GTFP for the observations.

Super-SBM model

The Data Envelopment Analysis (DEA) is an effective method for measuring the relative efficiency of decision-making units (DMUs) (Charnes et al., 1978). Tone (2001) introduces the slack-based measure (SBM) model, which fundamentally differs from radial approaches (e.g., CCR, BCC). This model explicitly incorporates both desirable and undesirable outputs while adopting a non-oriented, non-radial optimization framework, thereby mitigating efficiency overestimation in circular economy analyses (Yu et al., 2019). However, a recognized limitation of standard SBM is its inability to differentiate efficient DMUs with scores exceeding unity (Tone & Sahoo, 2004). The super-SBM model resolves this through hyperplane projection techniques, enabling precise ranking of Pareto-efficient units (DMUs) that cannot improve any input or output dimension without worsening others—a critical capability for analyzing green productivity where top performers often cluster near the frontier (Gökgöz & Erkul, 2019; Li et al., 2016). Recent methodological alternatives such as the epsilon-based measure (EBM) (Tone & Tsutsui, 2010), which hybridize radial and non-radial approaches, face empirical trade-offs. Pilot tests using the EBM-GML generated attenuated strategic alliance coefficients ($\beta = 0.008$ vs. super-SBM's $\beta = 0.019$) and unstable mediation paths, likely due to two factors. The first factor is divergence in slack sensitivity: the super-SBM's strict penalization of input and output slacks (Tone, 2001), particularly for undesirable outputs (e.g., emissions), imposes stronger environmental constraints than EBM's ε-parametrized framework (Huang et al., 2014). The second is limited frontier discrimination capacity: by projecting efficient DMUs beyond the convex hull, the super-SBM avoids the "efficiency ceiling" effect plaguing EBM (Li et al., 2016). Therefore, this paper adopts the super-SBM for primary analysis, with the EBM-GML results retained in robustness checks.

To incorporate energy inputs and ecological externalities (such as pollution emissions and resource depletion) into the analytical framework, we construct a production possibility set (PPS) that integrates sustainability constraints (Färe et al., 2005). Within this framework, by-products such as environmental pollution are treated as undesirable outputs. In this study, each firm is defined as a DMU to construct the production frontier. Assuming n DMUs each utilizes m inputs $X = (x_1, \ldots, x_m) \in R_m^+$ to produce s_1 desired outputs $Y = (y_1, \ldots, y_{s_1}) \in R_{s_1}^+$ while simultaneously generating s_2 undesirable outputs $B = (b_1, \ldots, b_{s_2}) \in R_{s_2}^+$.

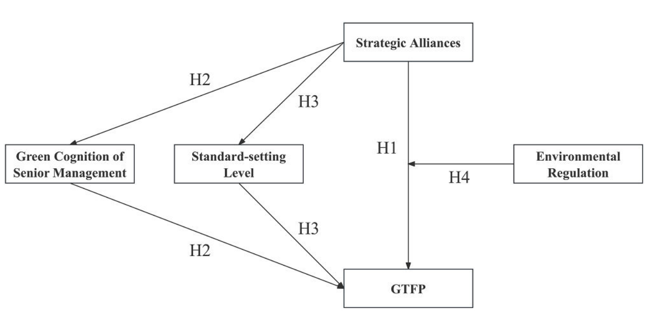

Fig. 1. Theoretical model.

At each period t ($t \in (1, 2, \ldots, T)$), the PPS for firm k ($k \in (1, 2, \ldots, K)$) can be described as:

$$\mathbf{P}\,(\boldsymbol{x},\ \boldsymbol{y},\ \boldsymbol{b}) = \left\{ \left(\boldsymbol{x}^{k,t},\ \boldsymbol{y}^{k,t},\ \boldsymbol{b}^{k,t}\right),\ \mathbf{x\ can\ produce}\ (\mathbf{y},\ \mathbf{b}) \right\} \tag{1}$$

where according to Färe et al. (2007), Eq. (1) satisfies the assumptions of the free disposability axiom, the weak disposability axiom, and the null jointness axiom.

According to Tone and Sahoo (2004), the super-SBM model is defined as Eq. (2):

$$\min \rho = \frac{\frac{1}{m}\left(\sum_{i=1}^{m}\frac{\bar{x}}{x_{ik}}\right)}{\frac{1}{s_1+s_2}\left(\sum_{w=1}^{s_1}\frac{\bar{y}_w}{y_{wk}} + \sum_{u=1}^{s_2}\frac{\bar{b}_u}{b_{uk}}\right)}$$

$$s.t.\begin{cases} \bar{x}_i \geq \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j,\ i = 1,\ 2,\ \ldots,\ m; \\ \bar{y}_w \leq \sum_{j=1,\neq k}^{n} y_{wj}\lambda_j,\ w = 1,\ 2,\ \ldots, s_1; \\ \bar{b}_u \geq \sum_{j=1,\neq k}^{n} b_{uj}\lambda_j,\ u = 1,\ 2,\ \ldots, s_2; \\ \lambda_j \geq 0, \bar{x}_i \geq x_{ik}, \bar{y}_w \leq y_{wk}, \bar{b}_u \geq b_{uk};\ j = 1,\ 2,\ \ldots,\ n\ (j \neq k); \end{cases} \tag{2}$$

where x_{ik}, y_{wk}, b_{uk} refer to inputs, desirable outputs, and undesirable outputs, respectively; λ represents the indicator weight, and ρ indicates the energy efficiency score of the DMU. If and only if $\rho \geq 1$, the DMU is considered effective. Otherwise, the DMU is in an inefficient state and needs to improve its inputs, outputs, or scale of production.

The ML and GML index

Chung and Färe (1997) propose the Malmquist–Luenberger productivity index (ML index) to estimate the dynamic changes of total factor efficiency, based on the contemporaneous benchmark technology set. A contemporaneous benchmark technology set of a group G_k at time t is defined as $P_{G_k}^t(x^t) = \{ (y^t, b^t),\ x^t \text{ can produce } (y^t, b^t) \}$, where $t = 1, \ldots, T$. This set constructs the reference production set at time t. Accordingly, the ML index between two consecutive periods is defined as Eq. (3):

$$ML_k^{t,\ t+1} = \left[\frac{1 + \vec{D}^t\left(x_k{}^t, y_k{}^t, b_k{}^t\right)}{1 + \vec{D}^t\left(x_k{}^{t+1}, y_k{}^{t+1}, b_k{}^{t+1}\right)} \times \frac{1 + \vec{D}^{t+1}\left(x_k{}^t, y_k{}^t, b_k{}^t\right)}{1 + \vec{D}^{t+1}\left(x_k{}^{t+1}, y_k{}^{t+1}, b_k{}^{t+1}\right)} \right]^{\frac{1}{2}} \tag{3}$$

where the $\vec{D}^G(\cdot)$ represents the directional distance function (DDF) associated with the contemporaneous benchmark technology set. While the ML index captures geometric mean efficiency changes, its reliance on adjacent-period frontiers presents two key limitations (Meng & Qu, 2022). First, sequential frontier shifts may cause technological discontinuity, where outliers distort efficiency trends, producing artificial regress or progress. Second, because efficiency scores are anchored to shifting benchmarks, cross-period comparability is compromised, undermining consistent longitudinal analysis.

To resolve these issues, Oh (2010a, 2010b) proposes the GML index, which unifies the reference technology across all periods. This is achieved by constructing a global benchmark technology set: $P^G = P^1 \bigcup P^2 \bigcup \ldots P^T$. As illustrated in Fig. 2, P^G envelops all contemporaneous PPSs, ensuring a fixed efficiency standard derived from the entire

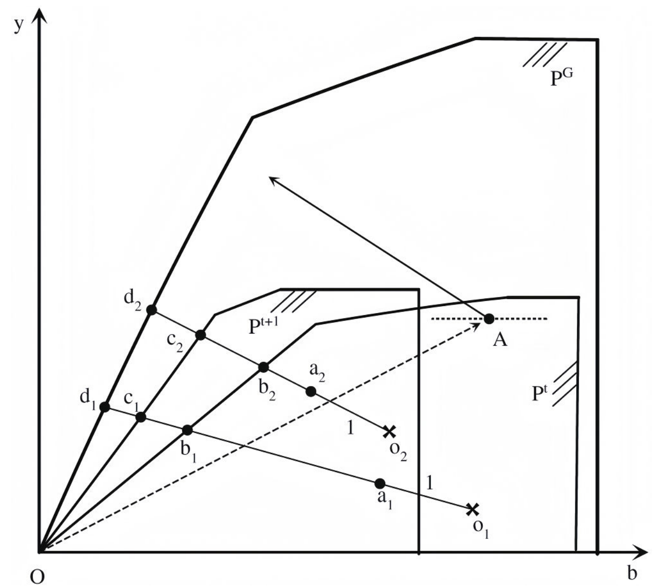

Fig. 2. Concept of the global Malmquist–Luenberger productivity index. Source: (Oh, 2010a).

panel data. The corresponding global DDF is then defined as Eq. (4):

$$\vec{D}^{G}\left(x^{t},\ y^{t}, b^{t}\right) = \max\left\{\beta \mid \left(y^{t} + \beta y^{t}, b^{t} - \beta b^{t}\right) \in P^{G}\right\} \tag{4}$$

where β quantifies the maximum feasible expansion of desirable outputs and contraction of undesirable outputs relative to the global frontier, thereby eliminating period-specific benchmark bias. By anchoring efficiency measurement to P^G, the GML index, defined as Eq. (5), inherently satisfies circularity and transitivity (Färe et al., 2005):

$$GML_{k}^{t,\ t+1} = \frac{1 + \vec{D}^{G}\left(x_{k}^{\ t},\ y_{k}^{\ t},\ \ b_{k}^{\ t}\right)}{1 + \vec{D}^{G}\left(x_{k}^{\ t+1},\ y_{k}^{\ t+1},\ \ b_{k}^{\ t+1}\right)} \tag{5}$$

Thus, $GML^{t,t+1} > (<) 1$, indicates total factor productivity improvement (decline), reflecting the capacity to produce more (fewer) desirable outputs and fewer (more) undesirable outputs across the unified technology set.

This integrated approach synthesizes four key phases: (1) constructing the global technology set P^G by pooling all DMU-period observations, (2) solving the global DDF $\vec{D}^{G}$ to quantify efficiency gaps relative to P^G, (3) computing intertemporal GTFP changes via the GML index, and (4) evaluating within-period efficiency frontiers using the super-SBM. Crucially, the non-radial super-SBM model evaluates firms' immediate technical efficiency in utilizing alliance-derived resources (reflecting the seizing capability to optimize existing green assets), while the GML index traces long-term productivity evolution (capturing the sensing and reconfiguring capabilities required to adapt to shifting environmental demands). Their combination operationalizes the dynamic capabilities theory's core proposition: strategic alliances enhance sustainability not merely through resource acquisition but via dynamic processes of opportunity identification, resource optimization, and systemic transformation. By avoiding radial measurement biases, the integrated methodology ensures robust testing of how alliances contribute to GTFP through both short-term efficiency gains and sustained capability development. The baseline GTFP values, constructed by integrating these metrics, are detailed in Section Dependent variable.

Empirical model setting

Baseline regression model

To examine the impact of strategic alliances on GTFP, this study adopts a baseline regression model with year and individual fixed effects to minimize endogeneity problems, as shown in Eq. (6).

$$GTFP_{kt} = \alpha_0 + \alpha_1 Alliance_{kt} + \alpha_2 Control_{kt} + \mu_k + \sigma_t + \varepsilon_{kt} \tag{6}$$

where $GTFP_{kt}$ represents the GTFP of firm k in year t; $Alliance_{kt}$ denotes the number of times that firm k participated in strategic alliances in year t; $Control_{kt}$ refers to a set of control variables, including *Size, Lev, Roa, SOE, Growth, InTangible, Top1* and *ListAge*. The term μ_k captures firm-specific fixed effects, accounting for unobservable time-invariant characteristics of each firm, while σ_t represents time-specific fixed effects, controlling for year-to-year variations that affect all firms equally. The random error term is denoted as ε_{kt}. Together, α_0 is the intercept term, α_1 and α_2 are the coefficients associated with the variables.

Generalized structural equation model (GSEM)

Given that both the independent and mediating variables in this study are count data and their logarithmic transformations—exhibiting significant dispersion—traditional fixed-effects models present limitations in handling such data. First, their stringent distributional assumptions may lead to estimation bias. Second, they struggle to accommodate complex, multilevel relationships simultaneously. The generalized structural equation model (GSEM) combines generalized linear model (GLM) estimation and structural equation model (SEM) estimation (Zhang & Zhang, 2018) and offers several advantages: (1) flexible specification of distributional assumptions appropriate for count data, (2) effective handling of measurement errors, (3) simultaneous estimation of multiple equations to accurately capture complex relationships among variables, and (4) provision of more robust parameter estimates through maximum likelihood estimation. Therefore, the GSEM is employed to estimate the parameters underlying the mediating effects between strategic alliances and GTFP. The GSEM is set as Eqs. (7) and (8):

$$Med_{lkt} = \theta_0 + \theta_1 Alliance_{kt} + \theta_2 Control_{kt} + \varepsilon_{kt} \tag{7}$$

$$GTFP_{kt} = \varphi_0 + \varphi_1 Alliance_{kt} + \varphi_2 Med_{lkt} + \varphi_3 Control_{kt} + \varepsilon_{kt} \tag{8}$$

where Med_{lkt} represents the mediator, and l takes the values of 1 and 2, corresponding to the green cognition of senior management and standard-setting level of firm k in year t, respectively. θ_0 and φ_0 denote the intercepts. The coefficients θ_1, θ_2, φ_1, φ_2, and φ_3 represent the parameters to be estimated. The other variables mean the same as the baseline regression model. In the testing process, one can conclude that a mediation effect is present only when the independent variable in Eq. (7) attains statistical significance, and the regression coefficient for GTFP in the mediator model of Eq. (8) becomes either statistically nonsignificant or markedly diminished relative to the baseline regression.

Moderating effect model

Based on the baseline regression model, this study establishes the following moderation effect test model, as shown in Eq. (9):

$$GTFP_{kt} = \tau_0 + \tau_1 + \ Alliance_{kt} + \tau_2 Eregulate_{kt} + \tau_3\ \left(Alliance_{kt} \times Eregulate_{kt}\right) + \tau_4 Control_{kt} + \mu_k + \sigma_t + \varepsilon_{kt} \tag{9}$$

In Eq. (9), $Eregulate_{kt}$ represents the environmental regulation intensity in the province where firm k is registered; $Alliance_{kt} \times Eregulate_{kt}$ represents the interaction term between strategic alliances and environmental regulation, indicating the moderating effect; τ_0 represents the constant term, while the remaining τ symbols represent the coefficients of the variables. The meanings of other variables are consistent with the previous definitions. If τ_3 is significant, this indicates that environmental regulation significantly moderates the relationship between strategic alliances and GTFP.

Variable selection

Dependent variable

In this study, *GTFP* is the dependent variable, reflecting the GTFP of each sample. It is constructed by integrating static efficiency levels with year-to-year productivity changes. The construction begins by establishing a pre-study baseline: the *GTFP* value for 2011 (the year preceding the analysis window) is normalized to 1.0, corresponding to the super-SBM efficiency score derived from the global production frontier. This allows the productivity changes that begin from 2012 to be anchored to a stable reference point unaffected by within-sample frontier shifts. Then, from this baseline, subsequent annual *GTFP* values are generated via sequential multiplication of the prior year's *GTFP* by the contemporaneous GML index. This calculation is expressed as $GTFP^t = GTFP^{t-1} \times GML^{t-1,t}$, which captures the productivity growth rate between consecutive periods. This intertemporal chaining procedure, implemented through MaxDEA software (Tone & Tsutsui, 2010), ensures temporal consistency by anchoring efficiency changes to the global benchmark technology set while preserving cross-sectional comparability.

Measuring *GTFP* requires the explicit definition of input–output variables aligned with the global production frontier P^G. Guided by the triple-bottom-line framework's integration of economic, environmental, and social dimensions (Elkington, 1997), our input–output variable selection operationalizes recent methodological advances in the measurement of green productivity (Liu et al., 2020; Meng & Qu, 2022). This dual anchoring ensures systematic capture of resource flows and economic–environmental trade-offs, balancing theoretical rigor with empirical applicability. Both input and output allocations adhere to the "proportional responsibility" principle in environmental accounting (Hertwich & Peters, 2009), which assigns resource burdens and pollution liabilities proportionally to economic activity contributions, ensuring methodological consistency with China's industrial reporting norms (Ministry of Industry and Information Technology of the People's Republic of China, 2014):

Input variables: (1) Labor input: total number of employees (in persons), (2) Capital input: net value of fixed assets (CNY), and (3) Energy input: estimated by allocating the industrial electricity consumption (MWh) of the city where the firm is registered to each firm proportionally based on its share of the city's total industrial workforce. For example, a firm employing 5 % of the city's industrial workers is assigned 5 % of the city's electricity consumption.

Output variables: (1) Desirable output: measured as annual revenue (CNY), and (2) Undesirable output: calculated in two steps. First, compute the city-level emission intensity for each pollutant (sulfur dioxide, industrial wastewater, dust) by dividing total emissions by the city's industrial GDP. Second, assign these intensities to each firm by multiplying the summed intensities by the firm's share of the city's industrial workforce. This reflects the firm's implied pollution burden given its economic scale within the local industrial ecosystem.

Independent variable

The independent variable, strategic alliances (*Alliance*), is operationalized as the annual count of active alliance engagements per firm. This approach follows the event-based measurement framework of Bodnaruk et al. (2013), which emphasizes strategic intent over temporal exposure. Alliance data are extracted from corporate announcements, with three criteria applied to ensure consistency:

(1) Strategic commitment: Excluding non-binding agreements, such as marketing partnerships (Contractor & Lorange, 1988). Alliances were coded as "strategic" if announcements explicitly mentioned technology co-development, equity investments, or multiyear resource sharing (Gulati, 1995).
(2) Temporal allocation: For alliances with explicitly disclosed durations, the engagement is counted annually from the initiation year (t) to the terminal year ($t + n$). For alliances without disclosed durations, studies indicate a median lifespan of 3–5 years (Reuer & Zollo, 2005; Schreiner et al., 2009). To ensure a conservative approach, we adopt the lower bound, assuming an active period of 3 years.
(3) Duplication checks: Merging overlapping announcements referring to similar alliances across the data source.

Mediating variables

In this study, *Greenknow* is tested as a mediator, reflecting the green cognition of senior management. Text analysis effectively measures management's cognition and can be applied to longitudinal data research (Duriau et al., 2007). Therefore, this study employs text analysis to measure the green cognition of senior management. Following Li et al. (2023), 17 keywords are selected based on three dimensions:

(1) Green competitive advantage cognition.[1] This dimension conceptualizes organizational capabilities to integrate environmental sustainability into core competitiveness, emphasizing strategic innovations that simultaneously enhance ecological performance and economic returns. Grounded in the natural RBV (Hart, 1995), it emphasizes strategic capabilities in pollution prevention and sustainable innovation.
(2) Firm social responsibility cognition.[2] This dimension encapsulates voluntary ethical commitments to environmental stewardship beyond regulatory compliance, reflecting firms' moral obligations to internalize ecological externalities. Rooted the in the stakeholder theory (Freeman, 1984), this dimension prioritizes ethical obligations beyond shareholder primacy.
(3) External environmental pressure perception.[3] This dimension captures institutional forces compelling firms to adopt environmentally compliant behaviors, including legal mandates, regulatory oversight, and public scrutiny. Informed by the institutional theory (DiMaggio & Powell, 1983), it highlights mandatory mechanisms such as environmental audits and policy enforcement that drive isomorphic organizational responses.

The green cognition of senior management is assessed using the logarithm of keyword frequency in the annual reports of the sample firms.

Another mediator in this study is the standard-setting level of a firm.

[1] Keywords: Energy conservation and emissions reduction; Energy efficiency and environmental protection; Low-carbon environmental initiatives; Environmental protection infrastructure; Environmental protection strategy; Environmental technology development.

[2] Keywords: Environmental protection philosophy; Environmental governance practices; Environmental education and technology development; Environmental pollution remediation technologies; Corporate environmental auditing; Environmental protection and pollution control; Environmental protection operations.

[3] Keywords: Environmental protection policies; Environmental protection-related legal frameworks; Environmental inspection mechanisms; Environmental management agencies; Environmental protection authorities.

This study differentiates standard-setting levels into two categories: local standard-setting level (*Standard_local*) and national standard-setting level (*Standard_national*). Both local and national standards are formal institutional arrangements led by the government, which effectively address the "free-rider" problem (Delcamp & Leiponen, 2014) prevalent in market-driven standardization. Moreover, they form a stable policy environment for green technology innovation, where national standards establish mandatory baselines under the "Dual Carbon" policy framework, while local standards reflect region-specific roadmaps for advancement (The State Council of the People's Republic of China, 2021). Together, they contribute to the enhancement of firms' GTFP. However, systematic differences exist between the two types of standards, such as institutional enforcement and technological adaptability. By comparing the distinct roles of local and national standards in promoting firms' GTFP, this study comprehends their specific contributions to green technology innovation and resource efficiency optimization, offering more targeted insights for policymakers and firm managers. Consistent with Zou et al. (2020), we quantify standard-setting levels using the logarithmic count of active local/national standards in which a firm participated during the measurement year. This approach captures the intensity and scope of a firm's engagement in standardization activities, and potential scale effects are mitigated through logarithmic transformation. In addition, currently effective standards ensure that the measurement reflects the up-to-date standardization process, aligning with the dynamic nature of technological and regulatory environments. The greater the number of active standards the firm is engaged in, the stronger the standard-setting level.

Moderating variable

In this study, *Eregulate* is the moderator, reflecting the environmental regulation intensity at the provincial level. Specifically, *Eregulate* is measured by the ratio of the total completed investment in industrial pollution control (10,000 CNY) to the industrial value-added (hundred million CNY) at the provincial level. The reasons for using provincial-level data rather than city-level data are owing to several important aspects of our research context. First, provincial governments act as pivotal enforcers of China's environmental policies, translating national guidelines into locally adapted implementation rules (Wang & Wheeler, 2005). Second, industrial firms in our sample operate across cities within provinces, making provincial regulatory pressure a more coherent strategic determinant than city-level variations. Finally, city-level pollution control data are inadequate, particularly in underdeveloped regions, whereas provincial-level data ensure balanced panel construction.

Critically, our investment-based measure of environmental regulation aligns with its theorized role as a market-aligned institutional incentive. By focusing on pollution control investments—proactive expenditures driven by firms' strategic responses—we capture how regulations internalize ecological costs into corporate decision-making. This contrasts with ex-post metrics (e.g., penalties, emission intensity), which reflect administrative enforcement rather than anticipatory adaptation (Chang et al., 2021). Consequently, our approach operationalizes the shift from state-led interventions to incentive-driven governance in China's environmental policy evolution.

To address potential scale bias caused by the small figure of the original ratio values, *Eregulate* is standardized using the Z-score method in the final dataset. This normalization ensures comparability across provinces and mitigates statistical distortions in subsequent analyses.

Control variables

Eight control variables were selected referring to relevant research (Lv et al., 2023; Zhang, 2021; Zhang et al., 2024). Firm size (*Size*) is measured as the natural logarithm of total assets (CNY). Leverage ratio (*Lev*) is defined as total debt divided by total assets, capturing a firm's financial risk. Return on assets (*Roa*) is calculated as net profit divided by the average balance of total assets during the period. Ownership type (*SOE*) is a binary variable where state-owned firms are coded as 1, otherwise 0. Firm growth (*Growth*) is measured using Tobin's Q. Largest shareholder ownership (*Top1*) is defined as the percentage of ownership held by the largest shareholder. Intangible asset intensity (*InTangible*) is measured as the ratio of the net value of intangible assets to total assets. Listing age (*ListAge*) is calculated as the natural logarithm of the number of years since the firm's initial public offering of stock.

Sample and data collection

Our study samples include Chinese A-share listed industrial firms. Industrial firms are selected for two primary reasons. First, industrial firms play a pivotal role in China's economy and are a primary target of national policies to promote green transformation. Investigating the GTFP of industrial firms can directly reveal their efforts and achievements in improving resource utilization efficiency and reducing environmental impacts, providing significant insights for policy formulation and firms' practices in green development. Second, owing to their technology-intensive nature and highly competitive pressures, industrial firms often rely on strategic alliances to acquire external resources and share technological knowledge. These characteristics make industrial firms a particularly suitable sample for examining the relationship between strategic alliances and GTFP. To ensure reliability and data availability, this study focuses on publicly listed firms. Specifically, based on the *Industry Classification Standards for Listed Companies (2012)* issued by the China Securities Regulatory Commission (CSRC), three main industrial sectors are considered: category B (mining), category C (manufacturing), and category D (electricity, heat, gas, and water production and supply).

Our study period was 2012–2022. We chose 2012 as the starting point because landmark governmental measures were introduced in this year, such as the 12th Five-Year Plan for Energy Conservation and Emission Reduction, which collectively signaled China's formal and resolute commitment to advancing green development nationwide. This timeframe made post-2012 data critical for studying regulation-related GTFP dynamics. Simultaneously, 2022 was chosen because the necessary data for this study were available up to 2022. Based on the initial research sample, the following screening procedures were conducted to construct a balanced panel dataset: (1) firms classified as ST, *ST, or PT were excluded; (2) firms whose industry classification had changed; and (3) samples with a wide range of missing variables were removed. After these adjustments, a final dataset comprising 9471 observations of 861 firms was obtained.

Data for labor input, capital input, and desired output in the calculation of GTFP were obtained from the annual reports of listed firms. However, energy input data were exclusively sourced from provincial statistical yearbooks and the *China Urban Statistical Yearbook*, while undesired output data additionally incorporated information from urban public bulletins. To address minor missing values at the province and city levels, the average growth rate over the past five years was applied to estimate the missing entries.

Strategic alliances data were manually collected by reviewing announcements published by listed firms on Sina Finance. For the *Greenknow* variable, Python software was employed to extract keyword frequencies from firms' annual reports. Raw data for *Standard_local* and *Standard_national* originated from the National Standards Information Public Service Platform (https://std.samr.gov.cn/), with final datasets systematically organized through Python-based web scraping techniques.

Moderating variable data were derived from the *China Statistical Yearbook* and provincial statistical yearbooks, while control variables were acquired from the China Stock Market & Accounting Research (CSMAR) Database.

Table 1
Descriptive statistics.

Variables	Obs	Mean	Std. dev.	Min	Max
GTFP	9471	0.797	0.639	0.014	31.778
Alliance	9471	0.173	0.645	0	15
Greenknow	9471	1.248	0.913	0	5.298
Standard_local	9471	0.012	0.099	0	1.609
Standard_national	9471	0.228	0.539	0	4.263
Eregulate	9471	0	1	−0.823	10.357
Size	9471	22.585	1.320	19.566	28.637
Lev	9471	0.415	0.187	0.008	1.334
Roa	9471	0.045	0.063	−0.661	1.285
SOE	9471	0.408	0.491	0	1
Growth	9471	1.973	1.276	0.681	21.296
Top1	9471	0.341	0.148	0.021	0.877
InTangible	9471	0.047	0.044	0	0.608
ListAge	9471	2.446	0.596	0.693	3.434

Source: Author's calculation based on R.

Table 2
Baseline regression results.

Variables	Dependent variable: *GTFP*			
	Model 1	Model 2	Model3	Model4
Alliance	0.022**(0.008)	0.020** (0.008)	0.023**(0.009)	0.019** (0.008)
Size		0.006 (0.017)		−0.009 (0.016)
Lev		0.259*** (0.066)		0.264*** (0.061)
Roa		0.880*** (0.110)		0.538*** (0.089)
SOE		−0.053 (0.041)		−0.058 (0.038)
Growth		0.032*** (0.006)		0.023*** (0.007)
Top1		−0.137 (0.101)		−0.147 (0.092)
InTangible		0.260 (0.221)		0.130 (0.212)
ListAge		−0.063* (0.035)		−0.045* (0.032)
Year/ individual	Control	Control	Control	Control
Adj. R^2	0.080	0.156	0.104	0.137
N	9471	9471	9471	9471

Source: Author's calculation based on R; $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$; standard errors in parentheses; same as below.

Empirical results and analysis

Data description

This study analyzes a panel dataset comprising 9471 firm-year observations.

Table 1 presents the descriptive statistics, revealing substantial variation across both dependent and independent variables. *GTFP* demonstrates significant dispersion across the sample, while *Alliance* shows considerable heterogeneity. The mediating and moderating variables exhibit distributions conducive to testing the proposed hypotheses. Control variables display appropriate variability, with firm ownership reflecting a balanced binary distribution. Overall, the dataset presents good variability and representativeness, providing a solid foundation for subsequent analyses.

Baseline regression

Our empirical analysis employs balanced panel data to address potential autocorrelation in error terms across temporal dimensions for individual entities. To elucidate unobserved heterogeneity, we implement a two-way fixed effects (TWFE) estimator that simultaneously controls for individual-specific and time-varying confounding factors. Model selection between fixed and random effects specifications was conducted through a Hausman test. The test assumes that if individual effects are correlated with the explanatory variables, the fixed effects model is preferred; otherwise, the random effects model is more suitable. In this study, the results of the Hausman test show a p-value $<$ 0.001, indicating that the fixed effects model provides more efficient parameter estimates in the baseline regression. Additionally, to address potential heteroscedasticity detected by the Breusch–Pagan test (studentized BP $= 28.186$, $p < 0.001$; Breusch & Pagan, 1979), we augment the TWFE estimator with weighted least squares (WLS), following Wooldridge's (2010) feasible generalized least squares framework. This two-step procedure first estimates inverse-variance weights from the squared residuals of a pooled model and then applies these weights within the TWFE specification to improve efficiency while retaining consistency. To ensure methodological coherence and comparability across analyses, all subsequent models employing fixed effects in this study adopt this WLS-adjusted approach (unless otherwise specified), systematically addressing heteroscedasticity in a unified manner.

Table 2 presents the baseline regression results incorporating both individual and year fixed effects. Models 1 and 2 display standard TWFE estimates, whereas Models 3 and 4 present WLS-adjusted results. The *Alliance* coefficient maintains statistical significance at the 5 % level across all specifications, with remarkable stability in magnitude ($\Delta < 0.004$). The WLS estimates yield tighter standard errors (e.g., the standard error for *Alliance* falls from 0.0084 in Model 2 to 0.0077 in Model 4—a 9.1 % reduction), enhancing statistical power without altering the economic interpretation. This persistent positive association between strategic alliance participation and GTFP, robust to both model specifications and heteroscedasticity corrections, empirically validates H1.

Mediation effects analysis

This study adopts the mediation analysis framework (Baron & Kenny, 1986) and enhances analytical rigor through GSEM (Table 3).

The methodological procedure comprises two sequential stages: First, the effects of strategic alliances on three potential mediators (green cognition of senior management, local standard-setting level, and national standard-setting level) were empirically assessed (Models 1, 3, and 5). Subsequently, changes in the direct effect of strategic alliances on *GTFP* were examined after incorporating these mediators (Models 2 and 4). The results demonstrate that the green cognition of senior management and local standard-setting level exhibit complete mediation effects, whereas the national standard-setting pathway is excluded from further mediation analysis owing to the non-significance of the initial association (Model 5).

These findings support H2 regarding the mediation mechanism of the green cognition of senior management while restricting support for H3 to the local standard-setting level rather than the national standard-setting level.

Moderation effect analysis

Table 4 presents the results of the moderation effect.

As shown in the table, environmental regulation (*Eregulate*) has a significant negative effect on GTFP, suggesting that strict environmental regulation may increase compliance costs, affect resource misallocation, or temporarily hinder firms' innovation. In contrast, the interaction term (*Alliance* × *Eregulate)* between strategic alliances and environmental regulation exhibits a positive coefficient, which is significant at the 5 % level. This result implies that strategic alliances mitigate the negative impact of environmental regulation and become a driving force of green innovation. Thus, the above findings support H4.

Robustness checks

To enhance the credibility of our empirical findings, we use five methods to conduct robustness tests. Table 5 shows the results of all methods except the placebo test.

Endogeneity treatment

The dual-directional relationship between alliance participation and

Table 3
Mediating effects analysis results.

Variables	Mediating variable: *Greenknow*		Mediating variable: *Standard_local*		Mediating variable: *Standard_national*
	Model 1	Model 2	Model 3	Model 4	Model 5
Alliance	0.033**	0.002	0.003*	0.001	−0.005
	(0.014)	(0.010)	(0.002)	(0.010)	(0.008)
Greenknow		−0.001			
		(0.007)			
Standard_local				−0.122*	
				(0.066)	
Standard_national					
Size	0.121***	−0.031***	0.007***	−0.047***	0.126***
	(0.010)	(0.007)	(0.001)	(0.007)	(0.006)
Lev	−0.008	0.244***	−0.002	0.237***	−0.069*
	(0.062)	(0.045)	(0.007)	(0.045)	(0.037)
Roa	0.276*	0.879***	0.052**	0.908***	−0.080
	(0.163)	(0.118)	(0.019)	(0.119)	(0.097)
SOE	−0.002	0.123***	0.001	0.122***	−0.010
	(0.022)	(0.016)	(0.002)	(0.016)	(0.013)
Growth	−0.123***	0.045***	0.004***	0.045***	0.003
	(0.008)	(0.006)	(0.001)	(0.006)	(0.005)
Top1	−0.118***	−0.048	−0.005	−0.030	−0.055
	(0.066)	(0.048)	(0.007)	(0.048)	(0.039)
InTangible	0.592**	0.401**	−0.038	0.454**	−0.490***
	(0.205)	(0.007)	(0.023)	(0.149)	(0.122)
ListAge	0.157***	−0.038**	−0.001	−0.027**	0.006
	(0.018)	(0.013)	(0.002)	(0.013)	(0.011)
N	9471	9471	9471	9471	9471
AIC	42,294.522		1103.306		32,494.468
BIC	42,459.110		1253.582		32,644.743

Source: Author's calculation based on R.

Table 4
Moderating effect analysis results.

Variables	Dependent variable: *GTFP*
Alliance	−0.001 (0.012)
Eregulate	−0.641** (0.278)
Alliance × *Eregulate*	0.636** (0.274)
Size	0.006 (0.017)
Lev	0.261*** (0.066)
Roa	0.884*** (0.110)
SOE	−0.053 (0.041)
Growth	0.032*** (0.006)
Top1	−0.137 (0.101)
InTangible	0.246 (0.221)
ListAge	−0.063* (0.035)
Year/individual	Control
Adj. R^2	0.157
N	9471

Source: Author's calculation based on R.

productivity presents a fundamental identification challenge: while participation in strategic alliances may enhance GTFP, firms with superior environmental performance may self-select into alliances owing to unobserved factors such as managerial foresight or institutional pressures. Moreover, unobserved confounders such as sector-specific innovation trends or environmental culture may simultaneously influence alliance participation and productivity. Hence, to address these concerns, we employ the difference generalized method of moments (difference GMM) estimator (Arellano & Bond, 1991), which resolves three key sources of endogeneity in dynamic panel data: (1) dynamic persistence in productivity caused by path-dependent technological investments, (2) time-invariant unobserved firm heterogeneity, and (3) reverse causality between alliance participation and GTFP. To further mitigate heteroskedasticity, we estimate the model with clustered robust standard errors at the firm level, which account for arbitrary within-firm variance patterns (Wooldridge, 2010).

The difference GMM approach models dynamic adjustments in green productivity by incorporating the lagged dependent variable ($GTFP_{k,t-1}$), capturing persistence in productivity trends that static models overlook. For endogenous regressors such as alliance participation (*Alliance*), the method instruments these variables using their lagged levels (from $t-2$ to $t-1$) in the differenced equation, isolating exogenous variation (Blundell & Bond, 1998). First-differencing eliminates time-invariant firm-specific effects (e.g., corporate environmental culture), while moment conditions leverage lagged instruments to control for time-varying omitted variables.

Table 5
Robustness test results.

	Difference GMM	Replace dependent variable	Replace independent variable	Add control variables
	Model 1	Model 2	Model 3	Model 4
Alliance	0.021**	0.008*	0.040**	0.018**
	(0.010)	(0.004)	(0.017)	(0.008)
Control variables	Control	Control	Control	Control
Year/individual	Control	Control	Control	Control
Adj. R^2	–	0.349	0.137	0.208
N	9471	9471	9471	9471

Source: Author's calculation based on R.

The validity of the GMM estimator is rigorously tested. The Sargan–Hansen test ($p = 0.105$) fails to reject the null hypothesis of instrument exogeneity, confirming the appropriateness of the overidentifying restrictions. Furthermore, autocorrelation tests validate the specification: first-order autocorrelation in differenced residuals (AR(1) $p = 0.751$) is expected in differenced models, while the absence of second-order autocorrelation (AR(2) $p = 0.819$) ensures no residual serial correlation. In Model 1, the positive and statistically significant coefficient of *Alliance* (coefficient = 0.021, $p < 0.05$) aligns with theoretical expectations, reinforcing the robustness of the baseline findings and strongly evidencing a causal interpretation of alliance participation on firm-level environmental performance.

Replace key variables

We conduct two additional tests by modifying key variable measurements and estimation approaches to enhance the robustness. On the one hand, we refine the calculation method for GTFP. Following the EBM model proposed by Tone and Tsutsui (2010), we compute the GML index. Then, this index is converted into GTFP through cumulative multiplication over time, consistent with the methodology described earlier. The fixed-effects estimation using this alternative GTFP measure (Model 2) demonstrates no material deviation from our original results. On the other hand, to mitigate potential data volatility in the alliance variable, we apply a logarithmic transformation to this variable (ln(*Alliance* + 1)) and re-estimate the model. Model 3 indicates that this non-linear transformation preserves the statistical significance ($p < 0.05$) and economic magnitude of the alliance coefficient. Critically, both robustness checks corroborate our baseline conclusion that strategic alliances exert a statistically and economically positive influence on the advancement of GTFP.

Inclusion of additional control variables

To address potential omitted variable bias and strengthen causal inference, we extend the baseline model by incorporating three theoretically grounded firm-level controls: board size, cash flow ratio, and capital intensity. The selection of these variables is motivated by the following considerations:

First, board size (*Board*, measured as the natural logarithm of the number of directors) serves as a proxy for corporate governance efficiency. Prior studies (e.g., Adams et al., 2010) demonstrate that larger boards may reduce decision-making agility in strategic initiatives owing to coordination costs, potentially moderating alliance participation effectiveness. Second, the cash flow ratio (*Cashflow*, defined as the operating cash flow scaled by total assets) captures financial flexibility, which influences firms' capacity to fund alliance-related investments and absorb associated risks (Jensen, 1986). Finally, capital intensity (*CAP*, calculated as total assets divided by operating income) reflects resource dependency patterns, as firms with higher fixed-asset ratios may exhibit greater reliance on external partnerships to optimize green technology adoption (Hillman et al., 2009).

Data for these variables are obtained from the CSMAR Database. We re-estimate Eq. (6) by augmenting the baseline specification with these controls. According to Model 4, the coefficient of *Alliance* remains significantly positive, confirming the robustness of our primary findings. More importantly, this extended analysis confirms that our main finding—strategic alliances positively contribute to the improvement in GTFP—is not simply a misleading result caused by ignoring differences among firms.

Placebo test

To validate that the results of the baseline regression are not incidental, we conducted a placebo test by simulating a scenario where the strategic alliance effect is artificially nullified. We randomly reassigned the binary variable *Alliance* (0 or 1) across firms while preserving its original sample proportion and retaining other variables unchanged. This randomization process breaks the causal link between strategic alliances and GTFP, allowing us to test whether the original results can arise spuriously.

After 2000 iterations of the baseline regression on the simulated datasets, Fig. 3 plots the kernel density distributions of the estimated coefficients and standard errors for *Alliance*, overlaid with a theoretical normal distribution curve (red line). The simulated coefficients exhibit a mean close to zero (coefficient = 0.0003, SD = 0.0131), with 95 % of estimates falling within the interval [− 0.024, 0.028]. The standard errors are tightly clustered around the mean (coefficient = 0.0132, SD = 0.0001), and both distributions align closely with the normal curve (Kolmogorov–Smirnov test, $p > 0.1$), showing no evidence of skewness or excess kurtosis.

These results confirm that the statistically significant relationship observed in the baseline model is unlikely to stem from random noise or unobserved confounders, supporting the robustness of our findings.

Further analysis

The impact of strategic alliances on GTFP may exhibit heterogeneity contingent on firms' geographic embeddedness and industrial attributes. To systematically explore these asymmetric effects, we conduct subgroup analyses through a grouped regression framework (Table 6). This approach aligns with institutional theory and the RBV. The former emphasizes how regional disparities in resource endowments and regulatory environments shape organizational outcomes (North, 1990), and the latter highlights industry-specific capabilities as moderators of strategic actions (Barney, 1991).

Regional heterogeneity

To assess regional variations, we classify firms into two categories based on their registered locations: (1) firms in the eastern region (e.g., Beijing, Shanghai, and Zhejiang) and (2) firms in the central-western region. Regression results reveal a striking divergence (Models 1 and 2). For eastern firms, the coefficient of *Alliance* is statistically significant and positive, indicating that strategic alliances contribute substantially to the enhancement of GTFP. In contrast, the effect is non-significant for central-western firms.

This phenomenon is explained by three possible factors. First, the divergent market environments between China's eastern and central-western regions shape distinct alliance dynamics. The eastern region's mature economy and hypercompetitive markets (Meng & Qu, 2022) compel firms to seek resource complementarity through alliances, particularly in sharing advanced equipment and real-time market intelligence. Such collaboration not only alleviates competitive pressures but also internalizes environmental compliance costs through joint green investments (Porter & Linde, 1995). In contrast, the fragmented markets and lax regulatory enforcement in the central-western region reduce firms' urgency to externalize innovation risks, leading to suboptimal utilization of alliance mechanisms for the enhancement of GTFP. Second, asymmetric policy interventions amplify regional disparities. Local governments in the eastern region proactively align fiscal tools (e.g., environmental subsidies and R&D) with green transition goals (Huang et al., 2022), effectively lowering entry barriers for alliance formation. This policy-driven institutional framework transforms alliances into vehicles for achieving scale economies in green technology deployment. Conversely, the central-western region's policy toolkit remains underdeveloped, failing to offset the inherent transaction costs of inter-firm collaboration—such as coordination complexities—which suppresses firms' willingness to engage in substantive alliance activities. Finally, the spatial distribution of industrial ecosystems affects alliance outcomes. Eastern industrial clusters, characterized by geographic proximity and specialized labor pools, enable tacit knowledge transfer through frequent face-to-face interactions. Alliances within such agglomerations naturally evolve into innovation collaboration, where iterative experimentation with green technologies becomes feasible (Ellison & Glaeser, 1999). However, dispersed firm locations and thin

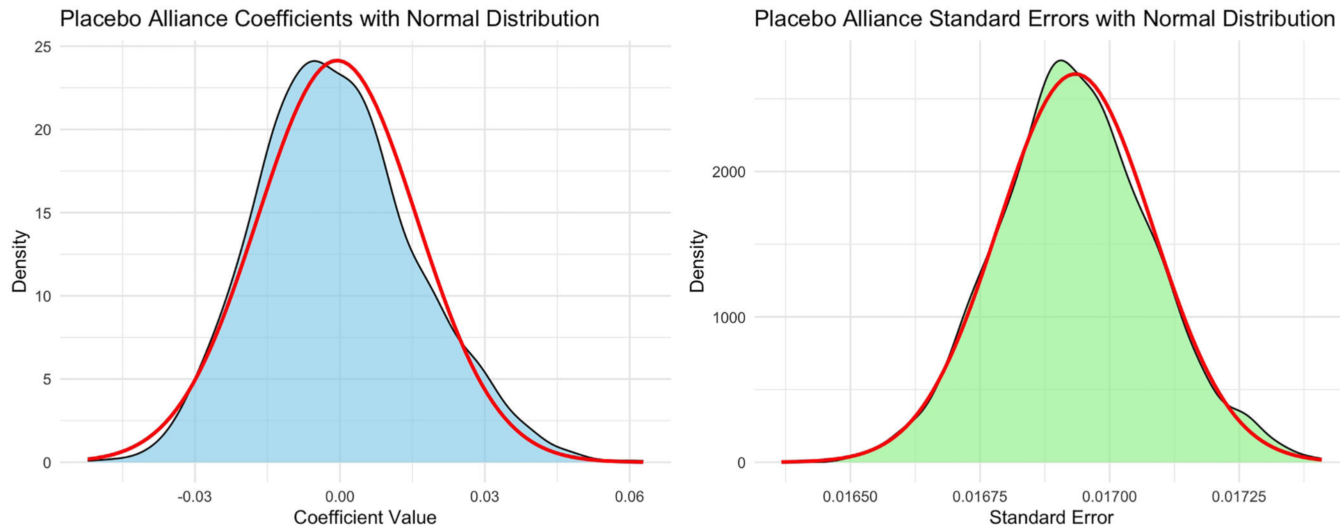

Fig. 3. Placebo test result.

Table 6
Heterogeneity analysis result.

Variables	Eastern region		High-pollution industry		High-tech industry	
	YES	NO	YES	NO	YES	NO
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Alliance	0.030**	−0.004	0.060***	−0.003	−0.008	0.064***
	(0.011)	(0.012)	(0.018)	(0.007)	(0.009)	(0.015)
Size	0.031	−0.045*	0.018	−0.003	0.014	0.004
	(0.023)	(0.024)	(0.034)	(0.016)	(0.019)	(0.030)
Lev	0.231**	0.301**	0.213*	0.314***	0.280***	0.198*
	(0.087)	(0.090)	(0.127)	(0.062)	(0.074)	(0.109)
Roa	0.995***	0.881**	0.758***	1.021***	0.533***	1.144***
	(0.141)	(0.164)	(0.212)	(0.102)	(0.122)	(0.183)
SOE	−0.017	−0.150**	−0.190*	0.054	−0.099**	0.009
	(0.052)	(0.065)	(0.079)	(0.038)	(0.043)	(0.075)
Growth	0.048***	0.002	0.042***	0.024***	0.065***	−0.017
	(0.008)	(0.009)	(0.012)	(0.006)	(0.007)	(0.011)
Top1	−0.060	−0.192	−0.247	−0.070	−0.297	0.046
	(0.140)	(0.128)	(0.191)	(0.095)	(0.119)	(0.163)
InTangible	0.599**	−0.447	0.684*	−0.163	−0.335	0.732**
	(0.293)	(0.297)	(0.410)	(0.212)	(0.276)	(0.334)
ListAge	−0.177***	0.046	−0.049	−0.051	−0.043	−0.069
	(0.047)	(0.049)	(0.070)	(0.032)	(0.040)	(0.056)
Year/individual	Control	Control	Control	Control	Control	Control
Adj. R^2	0.236	0.168	0.143	0.232	0.397	0.153
N	6325	3146	4323	5148	4556	4915

Source: Author's calculation based on R.

industrial networks in the central-western region elevate the costs of monitoring alliance partners and aligning strategic objectives. This spatial fragmentation traps alliances in low-trust, short-term contractual arrangements, stifling their potential to catalyze systemic improvements in GTFP.

Industry heterogeneity

We examine industry-level contingencies by stratifying the sample into four subgroups: high-pollution and non-high-pollution industries,[4] and high-tech and non-high-tech industries.[5] Results in Models 3–6 demonstrate significant heterogeneity. Specifically, the coefficient of *Alliance* is positively significant in industries facing stringent environmental regulation or with lower technological innovation capacity—similar to high-pollution and non-high-tech sectors—but is non-significant in their counterparts such as non-high-pollution and high-tech industries. These patterns imply two drivers: regulatory compliance and innovation substitution.

High-pollution firms face rigorous environmental pressures and regulatory requirements, effectuating a higher demand for technological upgrades. These firms rely more on strategic alliances to facilitate their green transition. Collaboration with alliance partners assists them in

[4] The classification is determined following the *Industry Classification of Listed Companies (2012)* revised by the CSRC and the *Industry Classification Management List for Environmental Compliance Verification of Listed Companies* issued by the Ministry of Environmental Protection (MEP).

[5] The classification follows the *Industry Classification Standards for Listed Companies (2012)* issued by the CSRC and the *National Key Supported High-Tech Fields.*

innovating environmental technologies and management practices at a lower cost compared to independent innovation and in adopting green technologies from their partners, enhancing their GTFP. In contrast, non-high-pollution firms may already possess relatively high environmental standards and advanced technologies; therefore, their involvement in strategic alliances has a limited marginal effect on the improvement in their GTFP. For high-tech industry firms, the primary purpose of engaging in strategic alliances is to share resources such as technology and knowledge. However, they already possess strong capabilities and resources for technological innovation, with their innovation activities primarily relying on internal R&D. Therefore, the role of strategic alliances is substituted by their internal innovation capacity, making the impact of strategic alliances on GTFP non-significant. Conversely, firms in non-high-tech industries face substantial gaps in technological innovation and upgrades. Hence, they are more likely to rely on strategic alliances to address their technological and managerial shortcomings, benefitting the obvious enhancement of GTFP.

Discussion

This study is the first to systematically evince the driving role of strategic alliances in enhancing firms' GTFP within the Chinese context, traversing the narrow cognitive framework of traditional literature that mainly focuses on the economic outcomes of alliances. While existing research reveals that strategic alliances enhance firm performances (Koval, 2021; Ozdemir et al., 2017), strengthen organizational capabilities (Lee et al., 2017; Subramanian et al., 2018), expand knowledge bases (Jansen et al., 2006; Li et al., 2010), and promote environmental compliance (Niesten & Jolink, 2020; Wang et al., 2024), these findings predominantly focus on the static effects of resource acquisition or passive adaptation to environmental regulation. In contrast, this study uncovers a structural functional leap of strategic alliances in the context of green economic transformation: alliances not only channel resource exchange but also provide systematic integration platforms for green innovation elements. Compared with Kim (2015) and Cho and Kim (2021), who explain traditional TFP and labor productivity, this study demonstrates that, when the alliance goals are embedded within the circular economy context, knowledge and technology spillovers preferentially flow toward core dimensions of GTFP, such as collaborative R&D in clean technologies and green supply chain restructuring, generating directed efficiency improvement.

Building upon the dynamic capabilities theory (Teece, 2007), this study examines the mediating effects of green cognition of senior management and standard-setting level in the relationship between strategic alliances and GTFP. The mediating role of the green cognition of senior management is significant, unveiling the cognitive "black box" of strategic decision-making—when managers engage with cutting-edge environmental practices through alliances, their cognitive frameworks undergo a paradigm shift from perceiving environmental costs as operational burdens to strategically reconceptualizing environmental initiatives as value-creation opportunities. This finding corroborates the upper echelons perspective that the personal traits of top executives affect strategic choices (Yang et al., 2024) and aligns with the conclusions that knowledge management and integration promote green development (Huang et al., 2025; Sun et al., 2022). However, a significant divergence exists in the mediating effect of standard-setting levels: while local standard-setting plays a significant mediating role, national standard-setting does not. This finding aligns with and extends the theoretical propositions of environmental federalism (Oates, 2002) while offering novel empirical evidence within the institutional context of China.

Three primary reasons can explain the abovementioned differences. First, the regulatory fit advantage. Building on Matisoff's (2008) regulatory proximity theory, local governments integrate regional economic and industrial characteristics into the standard formulation, ensuring a precise alignment between technical specifications and the local innovation ecosystem. This tailored approach significantly enhances the enforceability of local standards, making them more regionally adaptive (Zhang & Zhang, 2024). In contrast, national standards inherently prioritize universal applicability to accommodate cross-regional heterogeneity, effecting baseline requirements that often fail to address localized technical bottlenecks (Blind & Mangelsdorf, 2016). Second, divergence in enforcement incentives. While national standards elevate industry benchmarks through mandatory norms, their cross-regional implementation faces significant challenges. That's because substantial institutional transaction costs arising from multilevel administrative coordination occur, and firms participating in such national standard setting face high adjustment costs (Duysters & Lokshin, 2011). Conversely, local standards are embedded within government performance evaluations such as environmental inspection accountability, and supported by policy instruments such as tax incentives and green credit programs (Kostka, 2016). This government–firm collaborative pattern reduces institutional transaction costs, providing local firms with greater opportunities for technological innovation rather than merely focusing on regulatory compliance. Finally, the convenience of the knowledge spillover. Local standard setting establishes a multi-collaboration platform involving governments, firms, research institutions, and universities, among others, which accelerates the codification of tacit technical knowledge into shareable specifications while facilitating horizontal diffusion of best practices within industrial clusters (Blind & Mangelsdorf, 2013; Fang et al., 2016). More crucially, the dynamic revision stipulation inherent in local standards creates sustained pressure for technological system upgrading, effectively bridging the gap between R&D outcomes and market applications. This stipulation, which leverages standards as a platform for innovation, effectively mitigates the "standard-lag trap" identified by Delcamp and Leiponen (2014), where misalignment between standards and the latest technological advancements suppresses innovation. By accelerating the transition from R&D to market deployment, local standards facilitate the rapid transformation of the knowledge generated from alliances into productivity gains.

Additionally, this study investigates the moderating role of environmental regulation in the relationship between strategic alliances and GTFP. The positive moderation effect highlights the crucial role of strategic alliances in enabling firms to transform regulatory constraints into opportunities for collaborative innovation. This finding echoes the perspective of directed technical change proposed by Acemoglu et al. (2012) while emphasizing how external collaborative networks help firms overcome path dependence and actively steer the direction of technological transformation.

Moreover, the regional and industrial contingencies observed in our analyses align with the institutional theory's emphasis on spatial embeddedness (Marquis & Battilana, 2009) and sectoral regimes (Hoffman, 1999). The subdued alliance effects in the central-western region underscore institutional gaps in market coordination and policy implementation, while the more pronounced effects in high-pollution industries illustrate how increased regulatory stringency reconfigures alliance motives from voluntary cooperation to compliance-driven necessity. These boundary conditions highlight limitations in the assumption of alliance efficacy as a universal solution and call for a contingency perspective in sustainability alliance research.

Conclusion

The escalating environmental crises have caused the increasing recognition and adoption of the circular economy concept, with strategic alliances emerging as the key open innovation mechanism driving circular transitions. This study pioneers an investigation into how strategic alliances drive firms' GTFP, providing novel theoretical and empirical contributions to alliance and circular economy research. Using panel data from Chinese industrial listed firms from 2012 to 2022, this study employs a TWFE model to validate the positive impact of strategic alliances on GTFP at first.

Guided by the dynamic capability theory, the mediation analysis reveals that firms' enhancement of the green cognition of senior management and local (rather than national) standard-setting level serve as the critical mechanisms through which alliances promote GTFP. This finding underscores the importance of firms' proactive participation in regional standard setting, corroborating the role of decentralized governance in facilitating green transformation. Additionally, the moderating role analysis demonstrates that stronger environmental regulation amplifies the GTFP-enhancing effects of strategic alliances. This result aligns with the Porter hypothesis (Porter & Linde, 1995), highlighting the synergistic potential of policy–firm collaboration in driving green transformation.

Furthermore, our heterogeneity analyses reveal critical boundary conditions for the alliance-driven enhancement of GTFP. Regionally, strategic alliances exhibit stronger GTFP effects in China's eastern provinces, which is attributable to synergistic interactions between market maturity, policy intensity, and industrial agglomeration. At the sectoral level, alliances disproportionately benefit high-pollution industries confronting regulatory stringency and non-high-tech sectors constrained by innovation capacity gaps. These findings refine theoretical understanding by demonstrating how institutional frameworks and sectoral regimes affect the alliance–GTFP relation, transcending universal claims of "whether alliances matter" toward exploring "where and why they matter most." This spatial and sectoral characteristic offers a roadmap for targeted circular economy interventions.

By integrating the RBV, dynamic capabilities theory, and institutional theory, this study reconceptualizes strategic alliances as a multilevel platform that simultaneously optimizes resource allocation, enhances the green cognition of senior management (micro-level), reshapes local standards (meso-level), and responds to regulatory pressures (macro-level). This theoretical synthesis provides a holistic framework for understanding open innovation during transition to a circular economy and offers a practical pathway for aligning firms' strategies with Sustainable Development Goal 9 (industry, innovation, and infrastructure) and Sustainable Development Goal 12 (responsible consumption and production).

Theoretical and managerial implications

Theoretical implications

This study contributes to the theoretical research on strategic alliances by addressing the gap in understanding their role in GTFP within the context of the circular economy. Thus, our findings extend the traditional RBV approach, which predominantly focuses on profit-centric performance outcomes of strategic alliances. This study reveals the dual function of strategic alliances in the green economic transition: serving as means for knowledge spillovers and resource complementarity and as an effective approach for embedding environmental objectives into firms' strategies. By deeply integrating the RBV with the dynamic capabilities theory, this study proposes a sequential mechanism: alliance resource acquisition → dynamic capabilities renewal → green transformation implementation → GTFP improvement. This perspective offers a novel insight into understanding the strategic value of alliances in achieving circular economy goals.

Another key theoretical contribution of this study lies in our findings on the mediating mechanisms, which not only redefine the alliance-driven green transformation mechanisms but also extend the dynamic capabilities theory. First, our findings transcend the conventional paradigm of "resource–performance" by introducing the green dynamic capabilities construct that enriches Teece's (2007) framework in the circular economy contexts. Specifically, strategic alliances improve GTFP through two distinct mediators. First, the green cognition of senior management, which is not a passive response to external pressures but is actively reconstructed through benchmarking learning within alliance networks. This finding provides novel evidence for applying strategic leadership theory (Hambrick, 2007) in the field of circular economy. Second, the standard-setting level, which is not a static outcome but an organizational dynamic capability that continuously transforms alliance resources into influencing technological rules. This process exemplifies institutional entrepreneurship (Battilana et al., 2019), through which firms collaboratively construct standards, and offers new insight into the motives behind strategic alliances in the circular economy. Moreover, the identification of the standard-setting level as a pivotal mediator addresses a critical gap in the GTFP literature. While previous studies emphasize policy mandates or technological breakthroughs (Lv et al., 2023), this study demonstrates that firms' dynamic capabilities reshape industry ecosystems through standard setting, thereby driving green transformation from the market side in a bottom-up manner and addressing the limitations of policy instruments.

Finally, the moderating effect of environmental regulation validates the synergistic interaction between regulatory pressure and strategic response, which expands the empirical boundaries of strategic institutionalism (North, 1990). Concurrently, our findings reveal a positive moderation effect, which supports the Porter hypothesis (Porter & Linde, 1995) based on the Chinese context.

Managerial implications

Our findings offer actionable pathways for advancing China's circular economy through policy–firm synergies.

First, policymakers should embed the alliance-driven mechanisms across both market-based decarbonization tools and cross-regional standard harmonization. Regional governments can integrate an "alliance emission reduction coefficient" into carbon quota allocation rules—echoing the Beijing ETS pilot's use of emissions control coefficients to reward over-compliance—allocating additional quotas to alliance participants based on joint emission reductions or enabling cross-firm quota sharing (Zhang, 2024). In parallel, green finance demonstration areas should introduce "carbon-linked loans," enabling alliances to pool their quotas as collateral. This mechanism can enhance access to credit accessibility: for example, within the national green finance reform pilot zone in Chongqing province, a power generation firm successfully secured RMB 10 million in financing from a bank by pledging its carbon allowances (Chongqing Municipal People's, 2023). It can be complemented by integrating high-emission industries (e.g., steel and chemical) into carbon markets while providing targeted credit facilities. For instance, low-interest loans can be offered when alliances develop clear decarbonization roadmaps and meet the audit and disclosure requirements. Simultaneously, the National Development and Reform Commission has mandated unified technical standards, data protocols, and certification rules across the Yangtze River Delta economic region—an action that directly underpins the establishment of "green standard mutual recognition zones" in innovation corridors (National Development and Reform Commission, 2022). By harmonizing cross-regional processes through unified digital platforms, these zones can accelerate the adoption of alliance-developed benchmarks (e.g., energy-efficiency tiers), streamline multistakeholder certification systems, and maintain rigorous compliance via centralized audits. Such an approach leverages existing policy frameworks to ensure both efficiency and regulatory integrity in the diffusion of green standards.

Moreover, national open innovation platforms should prioritize the establishment of green technology trading hubs. For example, the Beijing Environmental Exchange has been operating a specialized China Certified Emission Reduction project and a green patent trading platform since 2008, standardizing transactions in emission reduction credits and circular patents. Supported by tax incentives, such as reduced income taxes on technology transfers, these hubs can accelerate alliance-driven innovation and market uptake.

For firm managers, advancing circular economy transitions necessitates a strategic integration of alliance-driven standardization, operational capacity-building, and institutionalized governance. First, proactive engagement requires coupling participation in cross-regional circular standards development, such as remanufacturing compliance frameworks, with structured executive training programs endorsed by regulatory bodies. These programs enhance firms' strategic alignment with evolving policy priorities while fostering technical competencies in green innovation.

Operationalizing such standards demands systematic cross-industry collaboration, including knowledge exchanges with frontrunners in ETS. By internalizing best practices such as closed-loop water flows, firms can translate policy experimentation into scalable operational efficiencies. Concurrently, advocating for the inclusion of alliance-developed standards in green finance catalogs, through alignment with internationally recognized certification equivalency frameworks (e.g., China's Environmental Labeling Program and the Global Eco-labelling Network), enables first-mover advantages in preferential financing.

Alliances must further prioritize mechanisms that synchronize decarbonization efforts with financial and operational incentives. To strengthen accountability, auditable circularity metrics, such as minimum recycled material thresholds, should be systematically embedded into governance frameworks. Simultaneously, participation in collaborative carbon collateralization initiatives can reduce compliance costs across alliance operations while incentivizing resource pooling for emission-intensive activities. Furthermore, alliances can establish carbon credit reserves, with revenue allocation pegged to each member's R&D contributions. This mechanism functions like a cap-and-trade market, rewarding higher emission reductions with greater financial returns, aligning individual innovation with collective decarbonization goals.

Limitations and future research

The limitations of this study provide avenues for future research to explore the evolving dynamics of green transformation.

First, this study focuses on Chinese industrial firms as a representative case of a developing economy. Although our results offer valuable insights for similar contexts, this context specificity stimulates three research extensions:

(1) Developed economy investigation: Conducting parallel analyses in developed economies to test whether alliance-driven green transformation mechanisms differ under mature regulatory systems and advanced innovation ecosystems.
(2) Cross-border comparative studies: Examining how variance in national sustainability policies (e.g., EU Carbon Border Adjustment Mechanism vs. China's Dual Carbon Goals) moderates alliance effectiveness through multicountry datasets.
(3) Global South knowledge transfer: Exploring whether alliance patterns identified in China can inform industrial decarbonization in ASEAN and African nations through policy benchmarking studies. Such studies can uncover context-specific strategies and inform global best practices in the green transformation.

Second, while our use of the dynamic capabilities perspective provides a strong theoretical foundation, the green transformation is inherently complex and may benefit from multiple theoretical lenses. Future studies can draw on institutional theory to explore how formal and informal institutional pressures shape alliance strategies, or use social network theory to examine the role of network position and embeddedness in facilitating green innovation diffusion. These alternative perspectives can identify additional mediating or moderating variables, deepening our understanding of the mechanisms through which strategic alliances influence green outcomes.

Finally, although we explore strategic alliances as a unified construct, they differ substantially in form and function. Future research should consider our findings as a basis to systematically investigate how different types of alliances, such as horizontal alliances among firms, vertical alliances with research institutions, or public–private partnerships, differ in their contribution to knowledge spillovers, technological innovation, and circular economy initiatives. A more granular analysis can identify which configurations of alliances are the most effective under varying organizational and environmental conditions.

Funding

This work was supported by the National Natural Science Fund of China [grant number 72272047]; the National Social Science Fund of China [grant number 22BGL291].

CRediT authorship contribution statement

Xinxing Wei: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gang Fang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Xianyun Yu:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

None.

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