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Change starts within: does managerial ability matter to green innovation?

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This study delves into the crucial link between managerial ability and green innovation. Motivated by the need for sustainable business practices and the pivotal role innovation plays in environmental sustainability, we identify a significant gap in the existing literature: the specific impact of managerial ability on fostering green innovation has not been adequately explored. Our research is anchored in the resource-based view, arguing that managerial ability is a strategic resource that can significantly influence a firm's capacity for green innovation. Our empirical analysis employs multiple regression analysis on a dataset of 2455 Chinese A-share listed companies from 2008 to 2022, examining the relationship between managerial ability and green innovation. To ensure a thorough investigation, we control for both firm-specific and year-specific fixed effects. Our findings reveal a significant positive correlation between managerial ability and green innovation, highlighting the critical role of managerial competencies in enhancing environmental innovation. Notably, subgroup analyses indicate that this relationship is more pronounced in state-owned enterprises, firms with a higher proportion of institutional investors, and in contexts with stricter environmental regulations and less developed product markets. These results not only fill the identified gap in the literature by providing empirical evidence of the impact of managerial ability on green innovation but also offer practical insights for businesses, managers, and policymakers looking to promote sustainable innovation.

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Introduction

"Green technologies—going green—is bigger than the Internet. It could be the biggest economic opportunity of the 21st century."

— John Doerr

Green innovation plays a crucial role in driving economic transformation and addressing the ever-changing environmental challenges (UNFCCC, 2023; Wurlod and Noailly, 2018). By fostering continuous innovation, we can better adapt to environmental changes while ensuring the sustainable and healthy development of the economy and society (Bina, 2013; Johnstone et al., 2008). Although the drivers of green innovation are akin to a complex labyrinth, challenging to decipher, their research is of utmost importance (Chen, 2008). Traditional studies typically explore these drivers from the perspectives of technology, market, institutions, and corporate strategy, analyzing policies and market changes to identify the factors that drive corporate green innovation (Brunnermeier and Cohen, 2003; Chang, 2011; Cleff and Rennings, 1999; Horbach, 2008). According to innovation diffusion theory, innovation spreads through interactions among individuals and groups within a social system, where the role of management is pivotal (Miller, 2015).

Existing research has explored the positive role of general management skills in promoting corporate innovation (Custódio et al., 2019). These skills help to stimulate innovative thinking, drive organizational change, and achieve strategic goals (Tether et al., 2005). However, the situation becomes more complex when it comes to green innovation. Green innovation is not just a matter of technical innovation; it also encompasses elements of environmental protection and sustainable development (Takalo and Tooranloo, 2021). This requires managers to possess not only general management skills but also a profound understanding and commitment to environmental protection, social responsibility, and sustainable development (Martínez-Ros and Kunapatarawong, 2019). Consequently, they need to control and allocate organizational resources to drive green innovation (Khanra et al., 2022).

The challenge of green innovation lies in its often-necessary transcendence of traditional business boundaries, involving more complex stakeholder management, higher initial costs, longer investment recovery periods, and the uncertainty of policy and market environments (Adams et al., 2016). Additionally, green innovation may require a change in the core operational methods of a business, including the adoption of new technologies, processes, and materials, which can encounter both internal and external resistance (Chen, 2008). Managers need to guide their businesses toward more sustainable and environmentally friendly directions while maintaining business performance and competitiveness (Hughes et al., 2018). This requires a perspective and managerial ability that goes beyond traditional management skills (Lin et al., 2021).

According to the resource-based view, managerial ability is seen as a unique resource of a company (Mahoney and Pandian, 1992), key to achieving green innovation. Managers can drive the development of green technologies and practices in their companies through effective decision-making and resource allocation (Wernerfelt, 1984). Additionally, the theory of transformational leadership underscores the role of management in guiding organizational culture and motivating employees, especially in inspiring environmental consciousness and innovative thinking among staff (Gumusluoglu and Ilsev, 2009; Jung et al., 2003). Furthermore, corporate social responsibility theories highlight the critical role of management in formulating and implementing a company's environmental policies and practices, which are directly linked to the company's green innovation performance (Garriga and Melé, 2004). These theories collectively emphasize that efficient managerial abilities can help companies better utilize and allocate resources to foster green innovation. However, quantifying managerial ability has been a challenge. In the past, scholars often relied on many factors outside the control of management to measure this variable. This situation continued until a new method was proposed by Demerjian et al. (2012), which is based on assessing how management enhances the revenue efficiency of a company. Through this approach, large-scale studies on managerial ability have become more reliable.

Meanwhile, there are perspectives in academia suggesting that the link between managerial ability and green innovation is minimal or non-existent. For instance, technological determinism emphasizes that green innovation is primarily driven by technological advancement and its own evolutionary logic, with limited influence from managerial decisions and abilities (Freeman, 1996). Market orientation theory argues that market demand and consumer preferences are the main drivers of green innovation, overshadowing the role of management (Cheng, 2020; Du and Wang, 2022; Wang, 2020). Additionally, institutional theory views corporate green behaviour as a response to external institutional pressures, such as laws, regulations, and industry standards, rather than because of proactive managerial strategies (Chen et al., 2018; Qi et al., 2021; Shu et al., 2016). These theories collectively suggest that the impetus for green innovation may more likely originate from external technological, market, and institutional environments, rather than depending on managerial ability.

Therefore, investigating the potential role of managerial ability in facilitating green innovation is an important research question that remains unresolved. To address this gap, we analyse data from 2455 Chines A-share listed companies covering the period from 2008 to 2022. We employ the data envelopment analysis (DEA), a method developed by Demerjian et al. (2012), which calculates managerial ability by distinguishing the impact of management on firm efficiency from the firm's overall efficiency. In line with previous research on innovation economics and green innovation (Amore and Bennedsen, 2016; Cui et al., 2023; Javed et al., 2023; Quan et al., 2021), we use two proxies, the number of green patent applications and green invention patent applications to measure corporate green innovation. After empirical testing, we reveal a significant positive correlation between managerial ability and corporate green innovation. This indicates that stronger managerial ability enhances a firm's capacity to acquire and utilize key resources, thereby more effectively promoting green innovation.

In addition to the main results, we conduct subgroup analyses based on firm characteristics and external factors. Our tests yield additional insights: (1) The enhancing effect of managerial ability on green innovation is more pronounced in state-owned enterprises and in companies with a higher proportion of institutional investors. (2) The positive influence of managerial ability on green innovation becomes increasingly significant in environments with higher environmental regulation. (3) In companies operating in less marketized product markets, the positive impact of managerial ability on green innovation is more distinctly observed. These findings provide a nuanced understanding of how various contexts can amplify the role of managerial ability in fostering green innovation.

To further mitigate concerns regarding our model, we employ propensity score matching (PSM), entropy balancing methods (EBM), and coarsened exact matching (CEM) in our regression analysis. These methods are chosen to enhance the robustness of

our findings by addressing potential biases. The results of these analyses confirm the significant positive effect of managerial ability on green innovation. Furthermore, we conduct a battery of additional tests. These tests include using alternative, independent variables and controlling for industry-fixed effects. We also include additional control variables followed by Quan et al. (2021), Cheng et al. (2023), W. Jiang et al. (2023a), and Zhang et al. (2023). Overall, the results of these additional robustness tests are consistent with our main findings.

Moreover, we conduct additional analyses to probe the influence of managerial ability on economic consequences, as measured by return on equity (ROE), and commitment to environmental, social, and governance (ESG), particularly in the context of green innovation. Our results reveal a significant and positive correlation between managerial ability and both ROE and ESG scores, emphasizing the benefits of managerial ability in driving financial success and promoting sustainable practices. More importantly, these outcomes suggest that green innovation plays a pivotal role through which managerial ability is translated into tangible economic and sustainable advantages. This pivotal role of green innovation highlights its importance as a conduit for managerial ability to yield economic and environmental consequences, underscoring its critical influence in the broader scope of our research insights.

This study makes theoretical contributions to the academic literature on management, corporate governance, and green innovation. While existing research has explored the impact of managerial ability on corporate performance (Andreou et al., 2013; Baik et al., 2020; Demerjian et al., 2013; Huang and Li, 2017; Vasileiou et al., 2022), there has been a lack of study on how managerial ability affects enterprises in specific areas, such as green innovation. By systematically exploring the relationship between managerial ability and green innovation, this study fills this gap and expands our understanding of the scope of influence of managerial ability. In addition, the findings support and extend the resource-based view, emphasizing that managerial ability itself can act as a crucial and unique internal resource, positively impacting a firm's green innovation.

Secondly, this study enriches the literature on the determinants of corporate green innovation (Roh et al., 2021; Roh et al., 2022; Roh and Yu, 2023). While the use of data envelopment analysis (DEA) to measure managerial ability is well established, our study's application within the Chinese context, particularly in relation to corporate green innovation, offers new insights (Lee and Roh, 2023a, 2023b; Liang et al., 2023; Lu et al., 2023; Roh et al., 2023). Furthermore, by using a variety of robustness testing methods such as PSM, EBM, and CEM, this study ensures the reliability and generalizability of its results. This provides a reference for future research in related fields.

Thirdly, our findings emphasize the importance of corporate governance structure and ownership in the field of green innovation. Companies with a high proportion of institutional investors, due to their long-term investment perspective and emphasis on sustainable development, are more inclined to support and drive management towards green innovation. This suggests that to promote corporate green innovation, one must consider not only managerial ability but also the influence of shareholder structure. This provides insights for businesses and policymakers on how to promote green innovation by optimizing shareholder structure and improving corporate governance.

Lastly, our findings offer valuable insights into promoting green innovation in different external environments, further deepening our understanding of the impact of external factors (i.e., environmental regulations and degree of marketization) and managerial ability. This indicates that managers and policymakers need to work together to foster more widespread and effective green innovation practices. For managers, this means they must adapt their strategies and innovation plans flexibly based on the intensity of environmental regulations and the level of market development where their firms operate. For policymakers, these findings highlight the importance of formulating and implementing environmental policies as well as fostering market development, as these policies and market conditions can significantly influence corporate green innovation behaviours.

The structure of the remaining parts of this paper is as follows: The section "Literature review and hypothesis development" offers a detailed review of related theories and previous studies, laying the theoretical foundation and developing hypotheses for this research. The section "Research method" introduces the data sources, sample selection, and the research model. The section "Empirical results" presents the findings from empirical analyses, discussing the relationship between managerial ability and green innovation. The section "Robustness tests" presents robustness tests on the results of the empirical analysis using multiple methods. The section "Additional analyses" presents additional analyses on the economic and environmental consequences of our baseline results. Finally, the section "Discussion and conclusion" summarizes the main findings of the study.

Literature review and hypothesis development

Managerial ability and green innovation. When exploring the impact of managerial ability on green innovation, the resource-based view (RBV) provides a powerful theoretical framework. According to this view, managerial ability is considered a unique resource of the company, crucial for achieving green innovation (Kraaijenbrink et al., 2010; Mahoney and Pandian, 1992; Wernerfelt, 1984). For instance, Assensoh-Kodua (2019) emphasized the key capabilities of the resource-based perspective in providing a competitive advantage in their study. The effectiveness of green innovation hinges critically on management's ability to adeptly integrate internal and external knowledge sharing, which not only influences organizational performance but also navigates the potential risks associated with knowledge transfer (Ben Arfi et al., 2018). Similarly, Baia et al. (2020) discussed the rarity of resources and capabilities as sources of competitive advantage and superior performance for companies. Additionally, transformational leadership theory highlights the role of management in guiding organizational culture and motivating employees, particularly in terms of influencing environmental awareness and innovative thinking among staff (Gumusluoglu and Ilsev, 2009; Jung et al., 2003). Albort-Morant et al. (2016) suggested that dynamic and ordinary capabilities significantly enhance green innovation performance, with dynamic capabilities directly improving innovation by adjusting learning relationships. This resonates with the study by Gibson et al. (2021), which explored the importance of incorporating community resources into the RBV. Corporate social responsibility theories also point out the critical role of management in formulating and executing a company's environmental policies and practices, which are directly linked to the company's green innovation performance, as noted by Andersen (2021).

Recent research underscores the pivotal role of coopetition strategy, open innovation, and digitalization capabilities in enhancing sustainable performance within business ecosystems (Y. Jiang et al., 2023b; Lee and Roh, 2023a, 2023b; Lu et al., 2023). The synergistic effect of these strategies provides a nuanced framework for understanding how managerial abilities can foster an environment conducive to green innovation. Studies have shown that businesses that adeptly navigate the complexities of coopetition—collaborating with competitors while simultaneously competing—and leverage digitalization capabilities are

better positioned to achieve sustainable outcomes (Lee and Roh, 2023b). This suggests that the managerial ability to integrate and balance these strategic elements is crucial for driving sustainable performance and, by extension, green innovation. Furthermore, the interaction between inbound and outbound open innovation, facilitated by digital technologies, acts as a catalyst for sustainable performance, highlighting the importance of managerial ability in these areas (Lee and Roh, 2023a). Moreover, empirical evidence from studies on energy green efficiency across various regions further emphasizes the role of managerial ability in measuring and implementing energy efficiency initiatives, showcasing a direct link to green innovation (Lu et al., 2023).

However, quantifying managerial ability has always been a challenge. In the past, scholars often relied on many factors outside the control of management to measure this variable. For example, Grant and Verona (2015) discussed the challenges and potential solutions in assessing organizational capabilities in empirical research. The method proposed by Demerjian et al. (2012), using data envelopment analysis (DEA) to evaluate managerial ability based on revenue efficiency, marked a significant advancement in quantifying managerial ability in academic research. It facilitated more accurate comparisons across firms and industries and encouraged further studies on the interplay between managerial ability and corporate governance, enhancing our understanding of managerial efficiency and innovation.

Overall, RBV suggests that firms with superior managerial abilities can better leverage their resources towards innovative ends, including green innovation. Managers play a crucial role in resource allocation, strategic planning, and fostering an organizational culture that embraces sustainability. Their ability to sense, seize, and transform opportunities into green innovations is a critical driver of a firm's environmental performance and sustainable competitive advantage. By applying the RBV framework, we argue that managerial ability acts as a strategic resource that facilitates the development and implementation of green innovations. Thus, we propose the following research hypothesis:

H1a: Managerial ability is positively correlated with green innovation.

Meanwhile, there are also perspectives suggesting that the correlation between the two may be minimal or even non-existent. For instance, technological determinism advocates that green innovation is primarily driven by technological advancement and its own evolutionary logic, with limited influence from managerial decisions and capabilities (Freeman, 1996). This suggests that green innovation is more driven by technological developments rather than management strategies or decisions. According to technological determinism, the pace and direction of green innovation are determined by the inherent trajectory of technological progress, independent of individual managerial actions.

Market orientation theory emphasizes that market demand and consumer preferences are the main drivers of green innovation (Wang, 2020). This theory argues that the success of green innovation initiatives is more closely linked to a firm's ability to understand and meet market needs rather than the strategic competencies or insights of its managers, which indicates that corporate green innovation is more market-driven and has little association with the strategic choices and capabilities of management (Du and Wang, 2022). This contrasts with the theoretical framework of the resource-based view, attributing the impetus for green innovation more to external market factors than internal management resources.

Furthermore, institutional theory views corporate green behaviour as a response to external institutional pressures, such as laws, regulations, and industry standards (Chen et al., 2018; Qi et al., 2021; Shu et al., 2016). This means that even if management has the necessary abilities, a firm's green innovation actions may be more a reaction to changes in the external environment rather than the result of proactive managerial strategies. Recent research acknowledges that institutional pressures related to sustainability and green performance exert a significant influence on organizational behaviour and outcomes. For example, Liang et al. (2023) documented the ability of managers to innovate business models digitally in response to these pressures plays a mediating role in achieving green performance. This highlights the strategic importance of managerial responsiveness to external sustainability demands as a means to secure green innovation.

In summary, these theories collectively suggest that the drivers of green innovation may originate more from external technological, market, and institutional environments, rather than relying on managerial abilities and decisions. Based on these perspectives, we propose the following hypothesis:

H1b: Managerial ability is not correlated with green innovation.

Firm characteristics. The existing literature indicates that green innovation has its uniqueness in terms of environmental externalities and long-term aspects, characteristics that distinguish green innovation from regular technological innovation (Brunnermeier and Cohen, 2003; Kim et al., 2021; Xiang et al., 2022). Environmental externality refers to the environmental benefits of a company's green innovation activities not being limited to the company itself but also positively impacting society and the natural environment (Xie and Teo, 2022). For example, when a company develops low-carbon emission technologies or sustainable production methods, these innovations not only enhance the company's environmental standards but also reduce environmental pollution for the entire society, bringing widespread environmental benefits. The existence of such externalities means that relying solely on market mechanisms may not be sufficient to fully incentivize companies to engage in green innovation. In this context, the role of government becomes particularly crucial, with policy support and incentives such as tax reductions, subsidies, and R&D funding support becoming important tools to promote corporate green innovation (Cai et al., 2022; Huang et al., 2019). These measures can help alleviate the initial cost burden for companies in green innovation, reduce risks, and provide additional motivation, encouraging companies to participate more actively in green innovation.

In such a policy environment, the facilitating role of managerial ability in green innovation may be more pronounced in state-owned enterprises. State-owned enterprises are often closely linked to government policies (Lin et al., 1998). Therefore, when the government provides support and incentives for green innovation, the management of state-owned enterprises usually has stronger motivation and ability to respond to these policies. They can effectively utilize the resources provided by the government to formulate and implement green innovation strategies (Cheng et al., 2023). Moreover, due to the unique nature of state-owned enterprises, they often bear more social responsibilities, including environmental protection and sustainable development (Lin et al., 2020). Based on these viewpoints, we hypothesize:

H2a: The positive relationship between managerial ability and green innovation is more pronounced for state-owned companies.

On the other hand, the presence of institutional investors has a significant impact on a company's governance structure and strategic choices (Graves and Waddock, 1990). These investors often hold a longer-term investment perspective (McCahery et al., 2016), making them more inclined to support strategies that can bring long-term sustainable growth, such as green innovation (Aghion et al., 2013). Due to their typically deeper professional

knowledge and resources, institutional investors can more effectively evaluate and support management efforts in green innovation (Dyck et al., 2019). At the same time, the influence of institutional investors in corporate governance enables them to push management to focus on and implement green innovation through mechanisms such as site visits (Jiang and Yuan, 2018), and the board of directors (Tihanyi et al., 2003).

Furthermore, the sensitivity of institutional investors to risks and their emphasis on corporate reputation also prompt them to support companies that can effectively manage environmental risks and enhance brand value through green innovation (Amore and Bennedsen, 2016; García-Sánchez et al., 2020). In the current context where Environmental, Social, and Governance (ESG) standards are increasingly valued, this attitude of institutional investors is particularly important. Based on the literature review, the following hypothesis can be proposed:

H2b: The positive relationship between managerial ability and green innovation is more pronounced in companies with a higher proportion of institutional investors.

External factors. Existing literature indicates that external factors, such as environmental regulation and the degree of marketization, are crucial for understanding and analysing corporate green innovation (Qiu et al., 2020; Zeng et al., 2021; Zhang et al., 2020). For example, Liang et al. (2023) highlighted the role of institutional pressures on corporate green performance. These factors present different challenges and opportunities, but their mechanisms of action differ from internal firm characteristics, such as the type of ownership and the proportion of institutional investors. Therefore, considering these external environmental factors is indispensable when studying the relationship between managerial ability and green innovation.

In the context of high environmental regulation, companies face stricter environmental standards and potential compliance costs, which encourage them to seek innovative solutions to these challenges (Liu et al., 2021). In this scenario, managerial ability becomes a key factor for companies to adapt to environmental regulations and achieve green transformation (Chen et al., 2015). Highly capable management teams are more likely to identify and exploit opportunities for green innovation, effectively integrate resources to support innovative projects and navigate complex regulatory environments (Liao and Long, 2018). They can enhance corporate competitiveness and market performance through green innovation while complying with environmental regulations. Such management teams are usually better at understanding the long-term trends of environmental regulations and market demands, thus making forward-looking decisions (Yang et al., 2019).

Moreover, the level of environmental regulation also affects corporate investment decisions in green innovation (Huang and Lei, 2021). In a highly regulated environment, green innovation is not only a necessity for compliance but also key for maintaining competitiveness in the market (Rubashkina et al., 2015). Therefore, strategic decision-making of the management team is particularly important in promoting green innovation in such an environment (Qian et al., 2023). Based on the above analysis, the following hypothesis can be proposed:

H3a: The positive relationship between managerial ability and green innovation is more pronounced in the context of high environmental regulation.

On the other hand, when reviewing the level of product market development, existing literature reveals several key insights. Du et al. (2018) argued that in environments with a low level of product market development (i.e., low marketization index), companies face weaker market competition, and consumer awareness and demand for green products are less developed than in highly marketized environments. Additionally, the market's incentive and reward mechanisms for innovation are not sufficiently mature (Aghion et al., 2005). In this context, the ability of management plays an even more critical role in driving companies toward green innovation (Huang and Li, 2017).

Firstly, due to weaker external market incentives, companies deciding whether to invest in green innovation may rely more on internal driving forces (Eyraud et al., 2013). This implies that management teams with high capability are more likely to recognize the potential value and long-term necessity of green innovation, even in the absence of sufficient market incentives (Chen et al., 2015). They might proactively seek to improve operational efficiency, reduce costs, comply with potential future environmental regulations, or prepare for future market changes through innovation (Mishra, 2023). Secondly, strategic vision and managerial ability are particularly important in less marketized environments, where the choice of innovation paths and business models is more complex and challenging (Goldfarb and Xiao, 2011). Management needs to make effective resource allocation, market positioning, and technology selection in the absence of clear market guidance. Therefore, the following hypothesis can be proposed:

H3b: The positive relationship between management ability and corporate green innovation is more pronounced in less developed product markets.

Overall, the integration of transformational leadership and RBV provides a theoretical backdrop that supports the importance of managerial ability in driving green innovation. They suggest that the effectiveness of managerial ability in promoting green innovation is contingent upon both the internal attributes of the firm and the external environment in which it operates. This nuanced understanding acknowledges the complexity of green innovation as a multifaceted phenomenon influenced by a range of factors, reinforcing the value of examining these influences through a heterogeneity lens.

Research method

Data and sample. This paper utilizes A-share listed companies from 2008 to 2022 as the research sample. It is important to note that the calculation of the managerial ability index requires data from the previous year. Consequently, the actual sample data used for the years 2008–2022 is derived from the relevant data of the sample companies spanning from 2007 to 2022. With the implementation of new accounting standards in China in 2007, the initial year for this study is established as 2007 to ensure the comparability of financial information. The data selection process for this study is conducted as follows: (1) Excluding listed companies classified in the financial sector according to the Industry Classification Guidelines of the China Securities Regulatory Commission (revised in 2012); (2) Excluding companies listed as ST or *ST[1]; (3) Excluding samples with incomplete data. This process yields a final sample size of 2455 companies, amounting to 15,457 observations. To reduce the influence of outliers, this study applies a two-tailed winsorization at the 1% level to the continuous variables annually. Data regarding corporate green innovation is from the Chinese Research Data Services Platform (CNRDS), while other data is obtained from the China Stock Market Accounting Research (CSMAR) database, and Wind database.

Measures of variables

Independent variable: managerial ability. Although there are various methods to measure managerial ability, the approach by Demerjian et al. (2012) is widely adopted. They use data envelopment analysis (DEA) to calculate managerial ability by separating the impact of management on firm efficiency from the

overall efficiency of the firm. This method not only allows for the simple and intuitive calculation of operational efficiency for a large sample of companies while avoiding sample omission but also eliminates certain noise, thereby enhancing the reliability of research conclusions (Wang et al., 2017; Yuan and Wen, 2018). Therefore, we draw on the ideas of Demerjian et al. (2012) and adopt DEA to measure the managerial ability of listed companies in China. The specific steps are as follows:

In the first stage, DEA is used to calculate the firm efficiency. According to model (1), the maximum firm efficiency value is calculated for each company by industry (with the manufacturing industry classified at the secondary industry level). The company with the highest efficiency in the same industry is assigned a value of 1, and relative efficiencies for other companies are calculated, with values ranging between [0, 1]. The specific model is as follows:

$$\text{Max Firm Efficiency}_t = \frac{\text{Sales}_t}{V_1\text{COGS}_t + V_2\text{S\&M}_t + V_3\text{PPE}_{t-1} + V_4\text{Intang}_{t-1} + V_5\text{R\&D}_{t-1} + V_6\text{GW}_{t-1}} \quad (1)$$

In this model, Sales represents operating revenue, signifying the output of the company; while COGS (Cost of Goods Sold), S&M (Sales and Management expenses), PPE (Property, Plant, and Equipment), Intang (Intangible assets), R&D (Research and Development expenses), and GW (Goodwill) represent the inputs of the company, encompassing operational costs, sales and management expenses, fixed assets, intangible assets, R&D expenditures, and goodwill, respectively. The subscript t denotes the corresponding value for the listed company in the current year, and $t-1$ represents the value for the previous year.

Given that a firm's efficiency is influenced not only by managerial ability but also by the company's characteristics, the second stage involves conducting a Tobit regression of the company's efficiency by industry to eliminate the impact of company characteristics. The model for this stage is as follows:

$$\begin{aligned}\text{Firm Efficiency}_i = {} & \alpha + \beta_1 \ln(\text{Total Assets})_i + \beta_2 \text{Market Share}_i + \beta_3 \text{Free Cash Flow Indicator}_i + \beta_4 \ln(\text{Age})_i \\ & + \beta_5 \text{Business Segment Concentration}_i + \beta_6 \text{Foreign Currency Indicator}_i + \text{Year}_i + \epsilon_i\end{aligned} \quad (2)$$

In the model, Total Assets represent the total assets of the company. Market Share is the company's market share measured in percentage terms. Free Cash Flow *Indicator* is a dummy variable that takes the value of 1 when the company's cash flow is non-negative, and 0 otherwise. *Age* refers to the number of years the firm has been listed on the stock exchange by the end of year *t*. Business Segment Concentration indicates the sales concentration of the company's divisions. Foreign Currency Indicator is a dummy variable, which is assigned a value of 1 if the company operates subsidiaries overseas, and 0 otherwise. *Year* denotes a dummy variable for the company's fiscal year. The regression residuals ε obtained from Model (2) represent the managerial ability, which is denoted as MA in the subsequent text.

Dependent variable: Green innovation. Following the method of Quan et al. (2021), green innovation is quantified using two distinct metrics: the number of green patent applications (GP) and the number of green invention patent applications (GIP), both sourced from the Chinese Research Data Services Platform (CNRDS). Drawing on the approach of Xiang et al. (2022) and Zheng et al. (2023), we assess green invention patent applications (GIP), categorized as more advanced and demanding than other types, to reinforce the robustness of our analysis.

Empirical model. To test H1a and H1b, we construct the following model:

$$\begin{aligned}\text{GreenInnovation}_{i,t+1} = {} & \alpha_0 + \alpha_1 \text{MA}_{i,t} + \text{Controls}_{i,t} \\ & + \text{Year}_t + \text{Firm}_i + \varepsilon_{it}\end{aligned} \quad (3)$$

where GreenInnovation represents the state of corporate green innovation, measured by GP, and GIP, respectively; *MA* denotes managerial ability. Our primary focus is on the relationship between managerial ability and corporate green innovation, namely the sign and magnitude of the coefficient α_1. All standard errors in our regression results are adjusted for clustering at the company level.

Drawing on existing literature (Amore and Bennedsen, 2016; Bammens and Hünermund, 2023; Cheng et al., 2023; Quan et al., 2021; Sheng and Ding, 2023; Zhang et al., 2023), we select a series of indicators that significantly impact corporate green innovation as control variables. These include five economic factors (EV) and six governance factors (GV). The five economic factor variables are: SIZE (firm size), LEV (leverage), ROA (return on assets), GRO (firm growth), ASTURN (asset turnover); and the six governance factor variables are: EMPLOY (firm employees), LISTAGE (firm age), PAY (management compensation), DUAL (duality of CEO and chairman), TOP1 (ownership concentration), INDEP (independence of the board. Moreover, we also include controls for year- and firm-fixed effects[2]. Specific variable definitions can be found in Appendix A.

Empirical results

Descriptive statistics. Table 1 presents the descriptive statistics. The mean values for GP and GIP are 6.544 and 3.482, respectively, with standard deviations of 19.162 and 11.759, indicating that GP and GIP vary significantly, and the number of green invention patent applications for the sample companies is relatively low. The mean value for MA is −0.006, suggesting that the overall managerial ability of the sample companies is on the lower side. The average size of the sample companies is 22.238, which is ~4.5 billion RMB when converted. Additionally, the average number of EMPLOY in the sample companies is 7.859, ~2589 when converted[3].

Baseline regression analysis. Table 2 reports the main regression results. The dependent variables are the number of green patent applications (GP) and the number of green invention patent

Table 1 Descriptive statistics.

Variable	N	Mean	SD	P25	Median	P75
GP	15,457	6.544	19.162	0.000	1.000	5.000
GIP	15,457	3.482	11.759	0.000	0.000	2.000
MA	15,457	−0.006	0.142	−0.103	−0.016	0.081
SIZE	15,457	22.238	1.280	21.340	22.050	22.940
EMPLOY	15,457	7.859	1.194	7.041	7.730	8.565
LEV	15,457	0.410	0.195	0.256	0.403	0.554
ROA	15,457	0.038	0.076	0.016	0.039	0.068
GRO	15,457	0.231	2.289	0.002	0.129	0.289
LISTAGE	15,457	10.013	6.697	5.000	8.000	14.000
PAY	15,457	14.543	0.743	14.047	14.502	14.973
ASTURN	15,457	0.624	0.463	0.374	0.531	0.744
DUAL	15,457	0.303	0.460	0.000	0.000	1.000
TOP1	15,457	0.327	0.144	0.217	0.305	0.417
INDEP	15,457	0.376	0.055	0.333	0.333	0.429

Table 2 Baseline results.

Variables	GP	GP	GIP	GIP
	(1)	(2)	(3)	(4)
MA	3.458**	3.906***	2.694***	2.957***
	(2.568)	(2.780)	(3.130)	(3.216)
SIZE		2.598***		1.393***
		(3.950)		(3.485)
EMPLOY		1.777***		1.143***
		(3.150)		(2.732)
LEV		−3.850***		−2.772***
		(−2.743)		(−3.027)
ROA		1.592		0.090
		(1.350)		(0.126)
GRO		−0.033		−0.019
		(−1.612)		(−1.006)
LISTAGE		−1.360		−0.524
		(−0.614)		(−0.471)
PAY		0.302		0.317
		(0.485)		(0.693)
ASTURN		−0.956		−0.488
		(−1.492)		(−1.228)
DUAL		0.058		0.294
		(0.131)		(1.044)
TOP1		0.134		1.102
		(0.045)		(0.515)
INDEP		−1.180		−2.070
		(−0.231)		(−0.631)
Intercept	6.565***	−53.440**	3.499***	−34.061**
	(788.826)	(−1.986)	(657.671)	(−2.071)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
N	15,457	15,457	15,457	15,457
Adj. R^2	0.648	0.653	0.624	0.629

Estimates are based on OLS regressions with standard errors adjusted for heteroscedasticity and clustered at the listed company level, and numbers reported are regression coefficients with *t*-statistics in parentheses. **, and *** indicate statistical significance at the 5%, and 1% levels, respectively, based on two-tailed tests. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

applications (GIP). We use managerial ability (MA) as the test variable. Column (1) presents the regression results, including only managerial ability (MA), year- and firm fixed effects. In column (1), the coefficient of managerial ability (MA) is significantly positive (3.458, $P < 0.05$). In column (2), we control for economic and governance factors at the company level. The results of column (2) show that the coefficient of managerial ability (MA) is positive (3.906, $P < 0.01$). Similarly, we use the second metric (GIP) to measure corporate green innovation. The results in columns (3) and (4) show that managerial ability (MA) is positively correlated with the number of green invention patent applications at the 1% level. These findings suggest that, regardless of whether control variables are included, there is a significant positive correlation between managerial ability and corporate green innovation, supporting our hypothesis H1a and consistent with previous theoretical derivations.

Table 3 Managerial ability and firms' green innovation—firm characteristics.

Panel A: Analysis of firm ownership type

Variable	y = GP		y = GIP	
	(1)	(2)	(3)	(4)
	SOE = 1	SOE = 0	SOE = 1	SOE = 0
MA	12.224***	2.476*	10.627***	1.714**
	(2.719)	(1.873)	(3.218)	(2.000)
Controls	Yes	Yes	Yes	Yes
Intercept	−97.114	−60.252***	−83.318**	−37.684***
	(−1.646)	(−3.091)	(−2.136)	(−2.772)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	4282	11,175	4282	11,175
Adj. R^2	0.695	0.601	0.678	0.530
Coefficient differences tests for *MA*				
Differences	9.748***		8.913***	
(*P*-value)	(0.000)		(0.000)	

Panel B: Analysis of institutional investor

Variable	y = GP		y = GIP	
	(1)	(2)	(3)	(4)
	HighIns = 1	HighIns = 0	HighIns = 1	HighIns = 0
MA	6.318***	2.297	5.249***	1.649*
	(2.626)	(1.444)	(3.325)	(1.690)
Controls	Yes	Yes	Yes	Yes
Intercept	−77.001	−35.613	−40.939	−20.774
	(−1.643)	(−0.818)	(−1.560)	(−1.109)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	7594	7863	7594	7863
Adj. R^2	0.677	0.607	0.650	0.566
Coefficient differences tests for MA				
Differences	4.021*		3.600***	
(*P*-value)	(0.067)		(0.009)	

Estimates are based on OLS regressions with standard errors adjusted for heteroscedasticity and clustered at the listed company level, and numbers reported are regression coefficients with *t*-statistics in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively, based on two-tailed tests. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

Firm characteristics. For testing hypothesis 2 (H2a and H2b), we create two subsamples along two measures that capture critical firm characteristics that may influence the relationship between managerial ability and green innovation—firm ownership type (Panel A), and institutional investor (Panel B).

We re-estimate our baseline model for a subsample analysis and report the results in Table 3. In Panel A, the sample is partitioned based on a dummy variable, SOE, that equals one if the firm is controlled by the government and zero otherwise. Our findings indicate that in SOEs, the facilitating role of managerial ability in green innovation appears to be more prominent. Hypothesis H2a is supported, aligning with our prior theoretical deductions. Since SOEs are usually closely linked with

Table 4 Managerial ability and firms' green innovation—external factors.

Panel A: Analysis of environmental regulation

Variable	$y = GP$		$y = GIP$	
	(1)	(2)	(3)	(4)
	HighEnvReg = 1	HighEnvReg = 0	HighEnvReg = 1	HighEnvReg = 0
MA	6.282***	1.432	4.540***	1.476
	(3.089)	(0.741)	(3.394)	(1.203)
Controls	Yes	Yes	Yes	Yes
Intercept	−24.313	−104.382	−15.621	−70.817
	(−1.253)	(−1.197)	(−1.267)	(−1.559)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	7915	7542	7915	7542
Adj. R^2	0.670	0.635	0.647	0.611
Coefficient differences tests for *MA*				
Differences	4.850**		3.064**	
(*P*-value)	(0.029)		(0.033)	

Panel B: Analysis of product marketization

Variable	$y = GP$		$y = GIP$	
	(1)	(2)	(3)	(4)
	HighMarket = 1	HighMarket = 0	HighMarket = 1	HighMarket = 0
MA	2.148	6.536***	1.973*	4.573***
	(1.216)	(2.900)	(1.832)	(3.118)
Controls	Yes	Yes	Yes	Yes
Intercept	−85.895	−27.774	−54.848*	−17.209
	(−1.507)	(−1.250)	(−1.874)	(−1.246)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	8160	7297	8160	7297
Adj. R^2	0.647	0.681	0.632	0.656
Coefficient differences tests for MA				
Differences	−4.388*		−2.600*	
(*P*-value)	(0.068)		(0.082)	

Estimates are based on OLS regressions with standard errors adjusted for heteroscedasticity and clustered at the listed company level, and numbers reported are regression coefficients with *t*-statistics in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively, based on two-tailed tests. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

government policies and objectives, this places the management in a critical position to understand and implement government environmental policies and green innovation directives. Effective managerial decisions help these enterprises better adapt to policy changes and utilize the resources and support provided by the government. Additionally, SOEs often have access to more resources, such as funding, technology, and talent. The ability of the management to ensure that these resources are effectively used for green innovation projects is particularly crucial. SOEs generally bear more social responsibilities and environmental missions, and the strategic planning and decision-making of the management play a central role in driving these enterprises to achieve their environmental goals.

Furthermore, to understand the role played by institutional investors, we further divide the sample companies into two groups based on the proportion of shares held by institutional investors. The grouping criterion was determined based on the median value for each year and industry. Based on this segmentation, we re-test our baseline model, and the analysis results are presented in Panel B of Table 3. These results show that in companies with a higher proportion of institutional investors, the positive relationship between managerial ability and corporate green innovation is more pronounced, thus supporting hypothesis H2b. This finding aligns with the theoretical views in the literature regarding the role of institutional investors (Dyck et al., 2019; Graves and Waddock, 1990). Institutional investors are often seen as more rational and long-term-oriented investors, and their involvement is commonly associated with better corporate governance, higher transparency, and stronger strategic planning capabilities (Aghion et al., 2013; McCahery et al., 2016). These attributes are particularly important in the field of green innovation, as it often requires substantial initial investments, long-term research and development processes, and a high sensitivity to market and environmental changes.

External factors. Based on the theoretical derivations in the section "External factors", we test how external factors affect the influence of managerial ability on corporate green innovation. We categorize the sample according to the intensity of environmental regulation (Panel A) and the development level of the product market (Panel B). The results of these tests are displayed in Table 4.

Firstly, to measure the intensity of environmental regulation, we utilize the amount of industrial pollution control investment per thousand yuan of industrial-added value in the province where the firm is located. Grouping is based on the annual median of environmental regulation intensity. We define a dummy variable (HighEnvReg) which is coded as one if the environmental regulation intensity of the firm's province exceeds the sample median and zero otherwise. The results from Table 4, Panel A confirm that in the

Table 5 Results based on propensity score matching, entropy balancing, and coarsened exact matching methods.

Variable	Panel A: PSM method		Panel B: Entropy balancing method		Panel C: Coarsened exact matching	
	(1)	(2)	(3)	(4)	(5)	(6)
	$y = GP$	$y = GIP$	$y = GP$	$y = GIP$	$y = GP$	$y = GIP$
MA	3.713*	3.897***	4.311***	3.332***	0.575**	0.618***
	(1.782)	(2.625)	(2.728)	(3.104)	(2.233)	(3.864)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Intercept	−22.766	−18.813	−54.675*	−38.210**	−89.094**	−57.930**
	(−0.793)	(−0.748)	(−1.883)	(−2.120)	(−2.411)	(−2.524)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3692	3692	15,457	15,457	15,392	15,392
Adj./Pseudo-R^2	0.658	0.651	0.615	0.586	0.651	0.628

Estimates are based on OLS regressions with standard errors adjusted for heteroscedasticity and clustered at the listed company level. Numbers reported are regression coefficients with *z*(*t*)-statistics in parentheses in the first (second) stage regressions. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively, based on two-tailed tests. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

context of high environmental regulation, managerial ability plays a more prominent role in driving corporate green innovation, aligning with hypothesis H3a. In such an environment, companies face stricter environmental standards and regulatory requirements, which not only increase operational costs but may also impact the firm's public image and market positioning. Consequently, managers need to demonstrate adaptability and foresight to ensure the company complies with current environmental regulations while maintaining a competitive edge through innovation. Our findings also suggest that under high environmental regulation, green innovation becomes more critical as it helps businesses reduce compliance costs and opens up new commercial opportunities. In this scenario, a highly capable management team can more effectively integrate resources and implement green innovation strategies, enabling the firm to meet environmental regulations and gain a competitive advantage in the market.

Furthermore, to assess the degree of product marketization, we employ the "Development Level of Product Market" indicator from the China Market Index Database. Grouping is conducted based on the annual median of this indicator, allowing us to categorize firms according to the development stage of their product markets. The results in Table 4, Panel B, reveal the impact of the product market's development level on the relationship between managerial ability and green innovation. We find that in environments with less developed product markets, the positive effect of managerial ability on corporate green innovation appears more pronounced, supporting hypothesis H3b. In such market conditions, external market incentives and drivers for innovation are relatively weak, so companies rely more on internal and strategic planning to drive green innovation. The high capability of the management team becomes particularly crucial in this context, as they need to identify and seize opportunities for green innovation in the absence of external drivers.

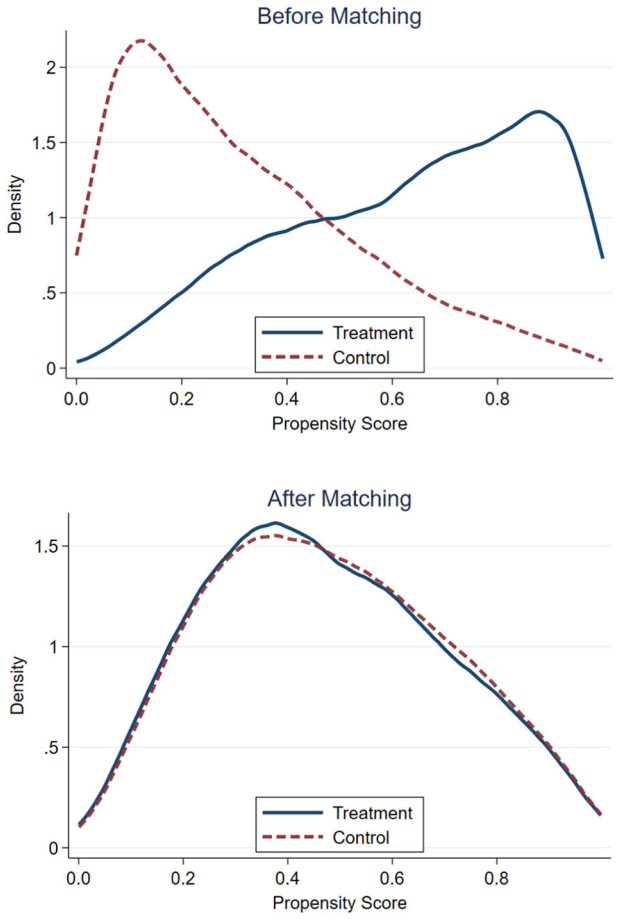

Fig. 1 Kernel density of propensity score before and after PSM. The figure presents the distributions of the propensity score before and after propensity score matching (PSM).

Robustness tests

Although this study controls for time effects and corporate individual effects in the baseline regression, thereby mitigating potential omitted variable issues (such as those variables that change over time and are related to both managerial ability and corporate green innovation), the conclusions may still be influenced by other endogeneity issues. To enhance the reliability of the regression results, the following tests were conducted.

Propensity score matching, entropy balancing, and coarsened exact matching methods. To address concerns that our linear OLS model might not capture certain differences influencing our results, we employ propensity score matching (PSM), entropy balancing methods (EBM), and coarsened exact matching (CEM) in our regression analysis. These techniques enhance the robustness of our findings by addressing potential biases. All the corresponding results are consolidated in Table 5.

First, we selected control variables from the main regression as covariates to estimate the propensity scores and matched the samples based on these scores. For the Green Patent outcome variable[4], we employ the 'calliper nearest neighbour matching'

Table 6 Other robust checks.

Variables	Panel A: Alternative measures for test variable				Panel B: Control for industry		Panel C: Control for additional variables	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	y = GP	y = GIP	y = GP	y = GIP	y = GP	y = GIP	y = GP	y = GIP
MA					4.061***	3.125***	4.524***	3.541***
					(2.939)	(3.538)	(3.096)	(3.798)
MA1	1.783**	1.549***						
	(2.445)	(3.140)						
MA2			0.585*	0.605***				
			(1.714)	(2.723)				
BOARD							1.002	0.298
							(0.434)	(0.191)
PERFORMACNE							1.074	0.674
							(1.402)	(1.397)
MALERATIO							0.01	−0.003
							(0.373)	(−0.202)
AVEAGEAGE							0.001	−0.002
							(0.007)	(−0.041)
CSRREPORT							0.703	0.350
							(0.952)	(0.697)
ENVREPORT							−0.804	−0.315
							(−0.336)	(−0.224)
KEYPOLLMONUNIT							0.377	0.261
							(0.754)	(0.818)
ISO14001							0.278	0.337
							(0.608)	(1.213)
RDSPENDSUMRATION							0.109**	0.086**
							(1.987)	(2.487)
PERGDP							0.000**	0.000***
							(2.086)	(2.703)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Intercept	−55.133**	−35.308**	−55.032**	−35.154**	−56.053**	−32.809**	−83.191***	−50.504***
	(−2.050)	(−2.153)	(−2.046)	(−2.143)	(−2.201)	(−2.378)	(−2.997)	(−2.771)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE					Yes	Yes		
N	15,457	15,457	15,457	15,457	15,457	15,457	14,492	14,492
Adj. R^2	0.653	0.629	0.653	0.628	0.654	0.630	0.671	0.649

This table presents the regression results for the two-stage regressions with instrumental variables. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively, based on two-tailed tests. Numbers reported are regression coefficients with *t*-statistics in parentheses. Standard errors are clustered at the client level. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

method for both the treatment and control group samples, conducting 1:1 matching within a calliper range of 0.01[5]. Figure 1 illustrates the effect before and after matching; there was a significant bias between covariates of the treatment and control groups before matching, but this bias was notably reduced after matching, indicating that propensity score matching eliminates characteristic differences between the two groups, enhancing the comparability of the samples.

The matched samples were then re-analysed using Model (3), and the regression results are shown in columns (1) and (2) of Table 5. The regression results demonstrate that, after controlling for firm characteristic heterogeneity, managerial ability (MA) still significantly promotes green innovation in listed companies, further supporting the core conclusion of our study.

Additionally, considering that the PSM method only matches individuals within the common value range and allows for repeated sampling, which may exclude unmatched samples and result in a reduction in the number of samples available for analysis. Following McMullin and Schonberger (2020) and McMullin and Schonberger (2022), we balance the mean and variance of the control variables across the treatment and control firms. The sample matched using the EBM is then re-regressed using model (3), and the results (see Table 5 Panel B) show that the coefficient of MA remains significantly positive, further validating the previous conclusions.

As a typical non-parametric data matching method (monotonic imbalance bounding), CEM reduces variable stratification by recoding, allowing for the application of exact matching algorithms in data processing (King and Nielsen, 2019). Compared to PSM, CEM lowers the imbalance between estimation error and total variance, ensuring matched groups improve sample balance, and is useful in limiting model dependence and estimation error in average treatment effects. Therefore, CEM is considered to balance reducing sample loss and improving matching quality (Iacus et al., 2009). To enhance the similarity between the treatment and control groups, we select SIZE, LEV, and ROA as the characteristic variables for CEM, apply the CEM method to construct paired samples, and re-run the regression. The results (see Table 5 Panel C) show that the conclusions of this study remain unchanged after matching.

Other robustness tests. To further ensure the reliability of our research, we conduct the following additional robustness tests. The results are listed in Table 6, which demonstrates the robustness of our research findings.

Table 7 Additional analyses.

Variable	Panel A: Economic consequences		Panel B: Environmental consequences	
	(1)	(2)	(3)	(4)
	ROE	ROE	ESG	ESG
MA	0.090***	0.092***	0.436***	0.440***
	(3.744)	(3.874)	(4.417)	(4.490)
GP	0.000***		0.006***	
	(3.885)		(7.519)	
MA*GP	0.001**		0.006*	
	(2.278)		(1.753)	
GIP		0.001***		0.008***
		(3.510)		(6.159)
MA*GIP		0.001*		0.010*
		(1.656)		(1.775)
Controls	Yes	Yes	Yes	Yes
Intercept	−24.313	−104.382	−15.621	−70.817
	(−1.253)	(−1.197)	(−1.267)	(−1.559)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	14,813	14,813	15,032	15,032
Adj. R^2	0.259	0.259	0.509	0.507

Estimates are based on OLS regressions with standard errors adjusted for heteroscedasticity and clustered at the listed company level, and numbers reported are regression coefficients with *t*-statistics in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively, based on two-tailed tests. All continuous variables are winsorized at the 1st and 99th percentiles. Variable definitions are presented in Appendix A.

(1) *Alternative independent variables*: Firstly, following the approach of Tian and Yang (2021), we use (1-MA industry rank in the current year/total number of companies in the industry that year) as an alternative measure for managerial ability. Secondly, following the study by Gan and Hu (2023), we divide managerial ability into a 0–1 scale annually by industry, based on the industry median of managerial ability for that year. The results of these alternative regressions are shown in columns (3)–(6) of Table 6.

(2) *Control for industry fixed effects*: To further refine our analysis, we incorporate industry fixed effects into the model (3). This retesting ensures that our findings are robust across various industry sectors. The revised results are displayed in columns (7) and (8) of Table 6.

(3) *Control for additional variables*: Apart from our control variables, other factors may influence corporate green innovation. We refer to the studies of Quan et al. (2021), Cheng et al. (2023), W. Jiang et al. (2023a), Zhang et al. (2023) and add BOARD (board size), PERFORMANCE (sales per employee), MALERATIO (male ratio in management), AVEAGEAGE (average age of the top management team members), CSRREPORT (disclosure of environmental information in CSR reports), ENVREPORT (separate disclosure of environmental reports), KEYPOLLMONUNIT (status as a key pollution monitoring unit), ISO14001 (ISO14001 certification), RDSPENDSUMRATIO (the proportion of R&D expenditure to operating revenue), and *PERGDP* (per capita GDP of the province) to model (3) and re-run the regression. The results are shown in column (9) and (10) of Table 6.

Additional analyses

To investigate the implications of managerial ability, we conduct additional analyses, focusing on the economic and environmental consequences associated with green innovation. Our findings, which are detailed in Table 7, shed light on how managerial ability can influence a company's financial performance and its commitment to environmental, social, and governance (ESG) standards. This exploration is critical to understanding the broader impact of our research findings.

(1) *Economic consequences*: Our further analysis examines the economic consequences of managerial ability, using return on equity (ROE) as the dependent variable. The regression results in Table 7, Panel A, show that managerial ability (MA) has a significant and positive effect on ROE. The inclusion of green patent variables—green patent and green invention patent—indicates that green innovation also positively contributes to ROE, with the interaction terms MA*GP and MA*GIP signifying incremental benefits when managerial ability synergizes with green innovation efforts. These findings underscore the importance of managerial ability in enhancing firm profitability through green innovation initiatives.

(2) *Environmental consequences*: Additionally, we examine the impact of managerial ability (MA) on environmental, social, and governance (ESG) performance. Using the Huazheng ESG rating[6], where ratings from AAA to C are assigned values from 9 to 1, we analyse how MA influences a firm's ESG score. The results demonstrate a significant positive effect of MA on ESG scores. Similar to the economic consequences, the positive impact of managerial ability on ESG performance is amplified in the presence of green innovation. These results are detailed in Table 7, Panel B, columns (3) and (4).

Discussion and conclusion

The core finding of this study is the significant positive correlation between managerial ability and corporate green innovation. We analyse data from 2455 Chinese A-share listed companies over a period from 2008 to 2022. Using a linear probability model (Fung et al., 2017; Wu and Ye, 2020), this research highlights the importance of managerial ability in driving green innovation, particularly pronounced in state-owned enterprises and companies with a higher proportion of institutional investors. Additionally, we reveal that external factors, such as environmental regulation and market development level, significantly affect this effect. In environments with stricter regulations and less marketized product markets, the positive effect of managerial ability is more pronounced. Our additional analyses demonstrate that managerial ability significantly boosts economic and environmental performances, particularly through green innovation.

Discussion. Our research extends the current understanding of green innovation by focusing on the pivotal role of managerial ability within Chinese A-share listed companies. This study's findings align with the broader literature that emphasizes the significance of open innovation and managerial strategies in fostering eco-innovation (Roh et al., 2021, 2023) and underscore the necessity of institutional approaches to drive corporate green innovation (Roh and Yu, 2023). In line with the resource-based view (RBV), our results reinforce the conceptualization of managerial ability as a critical, intangible asset that propels green innovation, supporting the theoretical contributions of Barney and Arikan (2005) and Holcomb et al. (2009).

By examining the structural relationships between managerial ability and environmental performance, our study corroborates findings from the Roh et al. (2022), which highlighted the instrumental roles of green supply chain management and green marketing innovation in enhancing environmental outcomes. Our research diverges by providing a nuanced analysis of how managerial ability, within varying regulatory and market contexts, specifically amplifies green innovation efforts. This distinction underscores our contribution to the literature on corporate governance and management's role in environmental sustainability.

Additionally, our study diverges from previous works by offering a detailed examination of the effects of managerial ability on green innovation across different ownership structures and market conditions, a relatively underexplored area in the literature. This nuanced approach allows us to uncover the varying degrees of impact managerial ability has under different external pressures, such as environmental regulation and market development levels. These findings not only align with but also extend the implications of transformational leadership theory (Gumusluoglu and Ilsev, 2009; Jung et al., 2003) by demonstrating management's critical role in implementing sustainable innovations. Moreover, the findings challenge certain traditional views, such as technological determinism (Freeman, 1996) and market orientation theory (Du and Wang, 2022; Wang, 2020), underscoring the indispensable role of management in the process of green innovation.

Significance and future directions. The significance of our findings lies in their practical implications for businesses, managers, and policymakers aiming to enhance environmental protection and sustainable development efforts. By identifying the conditions under which managerial ability most effectively contributes to green innovation, our study offers actionable insights for tailoring strategies to different corporate and external settings.

The findings reveal the critical roles of firm characteristics and external factors in shaping green innovation efforts. For businesses, the study suggests the need to optimize shareholder structures to support sustainable practices. For managers, it recommends adapting strategies to align with varying regulatory and market contexts, while for policymakers, it emphasizes the importance of designing and implementing policies that foster an environment conducive to green innovation. Overall, this study offers actionable insights for promoting effective and widespread green innovation practices across various corporate and external settings.

Looking forward, we acknowledge the importance of further exploring the heterogeneity of the relationship between managerial ability and green innovation across industries and regions, as well as the impact of managerial diversity on green innovation outcomes (Galbreath, 2019; Quan et al., 2021). These areas represent fruitful avenues for future research that can build upon our study's foundation, addressing the dynamic interplay between managerial capabilities, technological advancements, and market changes in shaping green innovation strategies and performance.

Data availability

The data that support the findings of this study are in the supplementary.

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Notes

1 ST stands for 'Special Treatment' and is used in the Chinese stock market to denote companies that have financial or operational difficulties. Specifically, ST is applied to companies with two consecutive years of financial losses, while *ST indicates companies facing more severe issues, such as the risk of delisting or significant regulatory violations. These designations serve as a warning to investors about the potential risks associated with these companies.

2 Following Fung et al. (2017) and Wu and Ye (2020), a linear probability model is employed when incorporating firm-fixed effects. This approach is used to mitigate the bias that can occur in a nonlinear limited dependent variable model, especially when group sizes are small.

3 To evaluate bias in the regression results due to multicollinearity among independent variables, a calculation of the variance inflation factor (VIF) was conducted prior to the formal regression to test for multicollinearity. The untabulated results indicate that the highest VIF value is 4.01, which is significantly <10. Hence, it is determined that there is no serious multicollinearity among the variables, allowing for the next step of regression.

4 Matching results using the Green Invention Patent as the outcome variable are the same.

5 Results of 1:1 matching within a 0.05 calliper range are consistent with the calliper range of 0.01.

6 The Huazheng ESG rating is chosen to measure corporate ESG performance. Compared to other rating systems, the Huazheng ESG rating covers a larger number of companies over a longer period. This rating is divided into nine levels, from highest to lowest: AAA, AA, A, BBB, BB, B, CCC, CC, C. These are assigned values from 9 to 1 in descending order, with higher values indicating better corporate ESG performance.

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Author contributions

All coauthors have made equal contribution to the paper. The specific contributions of each author are as follows: Yalin Jiang, Conceptualization, methodology, data gathering, analysis, writing review and editing; Wei Cai, Conceptualization, methodology, writing of original draft, writing review and editing; Yu Wang, Conceptualization, methodology, data gathering, analysis, writing review and editing.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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