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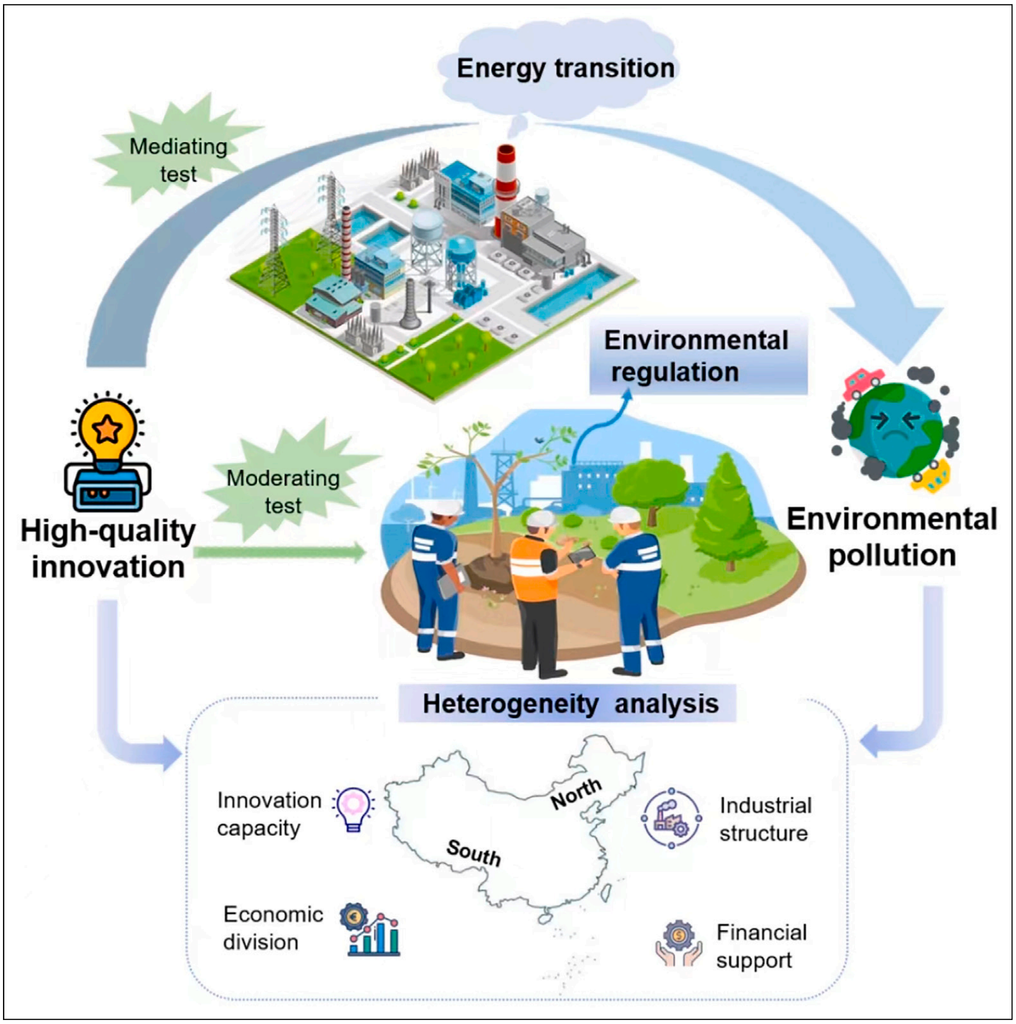

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Highlights

A composite high-quality innovation (HI) index is constructed

HI can effectively reduce the environmental pollution (EP)

The two-stage least squares method is employed

The impact between HI and EP is heterogeneous

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Mitigating environmental pollution in China: Unlocking the potential for high-quality innovation

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SUMMARY

The nexus between environmental pollution (EP) and technological innovation is crucial for achieving sustainable development. However, existing literature has paid less attention to the new form of high-quality innovation (HI) in environmental management. This paper uses panel data from 31 Chinese provinces from 2008 to 2020, employing the two-stage least squares method to investigate the relationship between HI and EP. The empirical results reveal that HI can effectively reduce the EP, which holds after multiple robustness tests, and this effect is more obvious in southern China. Meanwhile, HI drives clean and efficient energy transition and decreases EP. Moreover, increased environmental regulation weakens the influence of HI on EP. The major contributions of this study are constructing an HI index including innovation, human capital, and government support and examining its influence on EP in China. The findings encourage government to implement policies of innovation-driven transformation, energy conservation and emissions reduction.

INTRODUCTION

Environmental challenges, such as acid rain, soil degradation, and biodiversity reduction, have become some of the most pressing concerns in recent years.[1–3] The serious consequences of environmental pollution (EP) have adverse effects on ecosystem integrity, economic development (ED), and human health, posing a threat to the United Nations Sustainable Development Goals (SDGs).[4–7] For example, fatalities resulting from contemporary pollution such as ambient air and toxic chemical pollution have surged by 66%.[8] In addition, the exacerbation of global warming due to excessive carbon dioxide (CO_2) emissions has led to climate anomalies that threaten ecosystems' sustainability.[9] In response to the significant challenges in environmental management, the global community reached a consensus at COP26 and began to actively pursue sustainable development.[10,11] The pressing need for environmental protection has compelled countries to implement a series of policies,[12] promoting technological breakthroughs through high-quality innovation (HI) to achieve harmonious development.[13,14] Compared with general innovation, HI can further improve product quality and create higher economic value while eliminating outdated production and highly polluting enterprises.[15,16] Moreover, HI advancement can reduce dependence on traditional fossil fuel energy, enhance the effectiveness of waste use and treatment, and relieve pressure on the environment.[17,18] In summary, HI advances may continuously upgrade resource utilization and expedite the optimization of industrial and energy structures, advancing socioeconomic sustainable development.[19] Continued HI advancement can increase environmental protection and pollution control and enhance the living environment quality for rural and urban residents, which are beneficial for establishing a national ecological civilization.[20] Therefore, it is crucial to examine the relationship between HI and EP, explore the internal influence mechanisms, and provide policy insights for the government, enterprises, and other economic participants.

Following 40 years of reform and opening-up, China's economy has achieved remarkable economic progress that has attracted global attention.[21,22] However, severe environmental vulnerabilities have also been generated by rapid economic growth.[23,24] In 2018, 75.1% of the 338 cities in China exceeded air quality standards, with severe or higher levels of pollution occurring 2,721 times.[25] Moreover, the economic losses caused by pollution in China amounted to RMB 2 trillion in 2015, which was expected to rise.[26,27] There are several reasons behind these challenges. First, China's economic advancement has relied heavily on high-growth, energy-intensive industries,[28] and its industrial structure has not yet shifted to a more intensive model characterized by high technology, high added value, and low pollution.[29] The stage of China's ED driven by industry established serious energy imbalances in which energy consumption exceeded regeneration rates and environmental capacity.[30,31] Second, the current environmental protection control system in China is predominantly government-led.[32] Measures such as emissions trading, the establishment of environmental courts, environmental regulation (ER), and promotional incentives often rely on market efficiency and judicial effectiveness, which is limited to the short term.[33] Furthermore, government control methods

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and institutional arrangements are prone to facilitating pollution transfer to less regulated regions, exacerbating issues of uncoordinated regional development.[34] Vigorously promoting the cultivation of new drivers of economic growth and upgrading innovation are crucial for advancing the economic transition toward sustainable development.[24,35] HI emphasizes market subjectivity and aligns with China's emphasis on efficiency, fairness, and environmentally sustainable development.[7] Therefore, promoting HI development is beneficial for addressing environmental issues while establishing an economically viable green mode of production and lifestyle.

Various studies have been conducted regarding the relationship between technological innovation and EP, but the results have been inconsistent.[36–38] This inconsistency may be attributed to the use of single measures for technological innovation, which overlooks the distinction between general innovation and HI.[39,40] We argue that it is essential to define HI more accurately to explore its relationship with EP. This study makes the following contributions. First, China faces huge pressure to address EP, and has incorporated the United Nations SDGs into national development plans. These strategies strongly emphasize the role of technology development and adoption, especially HI, in balancing progress in resource conservation, economic growth, and environmental preservation. Second, the externalities of innovation on the environment remain inconclusive, which is associated with the gap in the standards of innovation development. General innovation advances technological progress and economic growth, which increases fossil energy consumption and damages the environment.[41,42] Therefore, distinguishing HI as a new form of innovation, rather than general innovation to examine its relationship with EP is crucial. This study constructs a new composite HI index, incorporating aspects of innovation, human capital, and government support. The new HI index comprehensively reflects the development level of innovation that considers social and economic benefits to effectively address the challenge of EP. Third, unlike previous studies on EP in China that have relied on single indicators such as CO_2 and sulfur dioxide (SO_2), this study constructs a composite index that includes gas, water, and solid waste using the entropy method. This new indicator reflects the diversity of pollutants in addition to considering differences in various pollutants' response to economic and technological progress. Finally, this paper employs the two-stage least squares (2SLS) method, accompanied by heterogeneity and robustness tests, to ascertain the role of HI in addressing EP. The findings will contribute valuable insights for the decision-making processes of authorities aiming to pursue green and sustainable development, particularly for different provinces in China that have exerted equivalent efforts.

RESULTS

Innovation quality in China

Innovation quality refers to innovations' actual technological impact, economic application value, and effectiveness.[43,44] China is currently undergoing a transition from prioritizing innovation quantity to focusing on innovation quality.[45] Enhancing the quality of innovation has become an essential aspect of implementing the nation's innovation-driven development strategy.[46] Some studies have begun to examine innovation quality in China, examining its potential influencing factors. Feng and Li[46] found that international technology spillovers, primarily from imports and outward foreign direct investment (FDI), have critical influence on Chinese innovation quality, with imports having a more substantial impact. Duan et al.[47] revealed an inverted U-shaped relationship between innovation quality and explicit and tacit knowledge-hiding behaviors, indicating that curvilinear correlations are favorably regulated by knowledge flow throughout an organization. Wang et al.[48] demonstrated that while high government investment has significantly increased the quantity of innovation in China, innovation quality has not significantly improved. Huang et al.[49] discovered that green finance prevents enterprises from pursuing low-quality innovation while simultaneously motivating them to foster HI in the long term. Xu et al.[16] showed that digitally inclusive finance has a more significant influence on innovation quality in China compared with motivating enthusiasm for innovation. Huang et al.[13] found that China's New Environmental Protection Law has a positive influence on the quantity of corporate innovation, but weakens innovation quality. Zhu et al.[50] determined that innovation quality is influenced by an imperfect patent system, unreasonable industrial policies, and the typical financial and temporal risks of long cycles. Zheng et al.[51] revealed that China's national innovation strategy effectively contributes to technological innovation quantity and quality. Han and Mao[52] showed that intelligent transformation improves innovation quality through human capital, research and development (R&D) expenditure, information sharing, and factor allocation.

Innovation and environmental management

The increasing appeal for healthier environmental has resulted in searching for reducing EP and pursuing sustainable development.[53] Among the measures and policies, technology and its innovation own positive externalities for environment, and can fundamentally solve EP problems, which attracts increasingly widespread attention.[54] Erdogan[55] demonstrated that increased technological innovation reduces carbon emissions among Brazil, Russia, India, China, and South Africa (BRICS) countries. Ma et al.[56] exposed the environmental quality-deteriorating impact of technological innovation among BRICS countries. Rej et al.[57] found that there is a unidirectional causality from environmental quality to environmental-related technological innovation in short-, medium-, and long-term frequency in India. Hossain et al.[58] and Hossain et al.[40] showed that technological innovation seems to emanate as a panacea for environmental degradation, such as CO_2, in the long-run in Mexico. Hossain et al.[59] discovered that eco-innovation positively impresses the load capacity factor, which helps the US maintain its environmental sustainability. Chen et al.[60] confirmed that there is a steady long-term relationship between technological innovations and ecological sustainability among newly industrialized countries.

However, there still exist controversial in the academic community due to differences in national environments, assessment methods, and time periods. Santra[61] discovered that the consumptions of energy and CO_2 in BRICS economies are improved by innovations. Dauda et al.[62] indicated that advanced innovation activities raise ecological deteriorations in BRICS countries while innovation decreases carbon emissions in G6 countries. Tobelmann and Wendler[63] reflected that ordinary innovation activities do not achieve the goal of reducing carbon emissions, but innovation practices measured by environmental patent applications do well. Gao et al.[64] indicated that climate change mitigation-related innovations improve environmental conditions while more environmental management-related innovations exert environmental quality-inhibiting impacts among BRICS countries. Das et al.[65] pointed out that the increased use of sustainable environmental technologies would bring decrease in the overall environmental sustainability in long-run across India due to greenwashing behaviors. Aytun et al.[66] showed that technological innovation does not have a statistically significant impact on the ecological footprint, and is not beneficial for achieving the sustainable development for middle-income countries.

For China, the relationship between technological innovation and environment attracts increasing attention. Some literatures argue that innovation plays an important role in coping with environmental problems. Ahmad et al.[67] demonstrated that technological innovation is an important driver in promoting sustainable development, revealing that innovation adds to economic growth without harmful effects on the environment. Liang et al.[68] showed that the breakthrough of technological innovation can reset the technologies trajectory, stimulate related innovations, and form new production system, which is beneficial for reducing pollution emission. Hasan and Du[69] showed that green financial innovation and green technical innovation are essential approaches for achieving environmental sustainability. Zhao et al.[70] found that positive effects have replaced negative ones as a result of China's technological innovation in terms of carbon emission efficiency. However, innovations sometimes raise concerns regarding environmental sustainability. Zhu et al.[71] found that innovation actions reflect that innovation worsens the ecology at the national standard in China on the basis of active and prominent coefficients. Khattak et al.[72] discovered that the ecological quality goals have not been reached with the help of technological innovation in China. Ke et al.[73] revealed that the improvement in technological innovation has a negative double threshold in influencing ecological footprint throughout China.

This study employs the 2SLS method. Previous studies have examined technological innovation and environmental issues using the time series method,[28,74] and ordinary least squares (OLS).[75] Compared with other methods, the 2SLS approach was created as a simpler model that requires less data and has useful applications for estimation.[76] 2SLS can handle issues of heteroskedasticity, multicollinearity, autocorrelation, and endogeneity, and performs better than time series and OLS methods.[77,78] In addition, 2SLS is an extended regression method to cover models that violate OLS assumptions of exogeneity so that the disturbance term of the dependent variable is correlated with the cause(s) of the independent variable(s).[79] As a result, 2SLS-estimated equations are more accurate in capturing the causal and feedback effects among a system's primary factors and the interactions between equations.[80] The superior performance of 2SLS has led to its widespread application in various fields, including financial markets,[81] the environment,[82] and corporate finance.[83]

Research gap

In the previous research, the specific effects of innovation on environmental deterioration are exceedingly complex,[54,66] particularly in the context of China.[71,84] The direction and degree of the influence of innovation on the environment largely depend on the level of innovation. Although the concept of high-quality development has been proposed in China, relevant literature that provides a clear definition of HI is lacking. Moreover, current studies have widely examined technological innovation, including green innovation, at the national level,[40,59] with a particular focus on China.[46,51] However, significant differences exist in ED level, population size, industrial structure, and other factors among different provinces, which may impact the performance of technological innovation. Therefore, this study measures China's HI among different provinces from innovation environment and output perspectives, demonstrating that HI is an internal driving force for environmental protection and sustainable development in China.

Theoretical foundation

Theoretical frameworks related to the relevant economic indicators can provide insights into the anticipated outcomes of the relationships between variables, transcending a mere data-driven exercise.[11] This subsection elucidates the connections between the pertinent variables by drawing inferences from existing theoretical hypotheses and previous empirical findings. The subsequent paragraphs offer comprehensive descriptions regarding the association between HI and EP, the mediating influence of energy transition (ET), and the moderating impact of ER.

China has recognized that innovation is a primary source of economic growth and social development.[85] In the past decades, strategic and symbolic innovation practices and programs have been implemented in China to pursue a higher quantity of innovation rather than emphasizing quality.[14,86] However, as China's economy transitions to high-quality development, improving innovation quality has attracted increased attention.[63,87] HI can stimulate technological progress, optimize industrial structure, and improve waste recycling efficiency, contributing reduced EP.[88,89] First, HI can advance structural optimization, reducing EP. It better reflects innovation capabilities, which can generate high economic value, ultimately promoting more rapid value chain advancement.[90,91] This may expedite industrial structure renewal and adjustment, leading to the transformation of the ED toward a more intensive, low-pollution mode and reducing EP.[92] Second, HI accelerates technological progress, leading to more effective EP reduction. HI can considerably improve production and pollution control technology, lowering pollutant emissions and improving efficiency in waste recycling and utilization during the production process, ultimately reducing EP intensity.[93] Therefore, this study proposes hypothesis 1.

Hypothesis 1: High-quality innovation can effectively reduce the environmental pollution.

This study examines whether HI can reduce EP in China by promoting ET. Energy is the foundation of economic and social advancement, and excessive energy consumption degenerates ecological quality.[94] As China enters the stage of high-quality advancement, the nation needs the support of a clean energy system, which motivated the new ET strategy.[95] With 6.37 Exajoule (EJ) of renewable energy consumed in 2018, China topped the global renewable energy consumption chart.[96] In addition to national strategies, saving and effectively using resources and energy in the manufacturing process depends on technological innovation,[97] particularly HI.[98] In addition, HI can improve thermal power generation efficiency, reducing demand for fossil energy such as coal.[99] Therefore, HI can optimize the energy structure more effectively, develop renewable greener and cleaner energy sources, decrease dependence on traditional fossil fuels, and ultimately reduce EP.[100] In summary, based on the mediating effect analysis, this study proposes hypothesis 2.

Hypothesis 2: High-quality innovation can effectively reduce environmental pollution by promoting energy transition.

ER can hinder HI effectiveness in reducing EP. Environmental laws and regulations require economic participants to invest in managing environmental impact, increasing the cost of production and pollution control, which reduces available R&D capital due to compliance costs.[13,101] The compliance cost effect makes it challenging for enterprises to improve environmental quality, as it reduces the motivation to learn from low-pollution and efficient counterparts and restricts the pace of innovation.[102] However, one study argued that appropriate ER is beneficial for improving innovation standards and increasing economic participants' capabilities to reduce pollution.[103] The innovation compensation effect arises when the income generated can cover the cost of implementing ERs entirely or in part,[104,105] which advances pollution control. Therefore, this article proposes hypothesis 3.

Hypothesis 3: Environmental regulation weakens the effect of high-quality innovation on reducing environmental pollution.

Data selection

Dependent variable: EP

The single pollutant cannot accurately represent the real situation of pollution. Referring to Zhao et al.[106] and Ren et al.,[107] we construct a comprehensive index of the degree of EP through the entropy method, which includes diversified pollutant emissions of waste-water per capita, waste-gas (SO_2) per capita, and waste-solid per capita. The data on industrial solid waste emissions are missing for some years, so we use the production instead of the emissions of industrial solid waste. This can accurately and scientifically reflect the actual EP situation in a certain area. In order to eliminate the influence of the order of magnitude and dimension, the original data are standardized as following.

$$x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \qquad \text{(Equation 1)}$$

$$e_j = -(1/\ln m)\sum_{i=1}^{m} p_{ij}\ln p_{ij}, p_{ij} = x'_{ij}\Big/\sum_{i=1}^{m} x'_{ij} \qquad \text{(Equation 2)}$$

$$w_j = (1 - e_j)\Big/\sum_{j=1}^{n}(1 - e_j) \qquad \text{(Equation 3)}$$

$$EP_i = \sum_{j=1}^{n}\left(w_j \times x'_{ij}\right) \qquad \text{(Equation 4)}$$

where x_{ij} is the jth pollution in i region. $\max(x_{ij})$ and $\min(x_{ij})$ represent the maximum and minimum pollutant emissions. e_j is the entropy. w_j is the weight. EP is environmental pollution index.

Independent variable: HI

To estimate the current advancement standard of China's HI, we compound an integrated index through the entropy method for the measurement of innovation, human capital and financial support from the government.[108,109] The reason is that the number of patents granted alone is not enough to accurately reflect the current China's level of HI. Regional educational quality, technological innovation level and government financial support can be regarded as an organic whole that better highlights China's actual level of innovation in the context of high-quality advancement. In detail, educational quality includes the number of universities per ten thousand people, the number of teachers per ten thousand people, and the number of students enrolled ten thousand people. Technological innovation level contains the proportion of technology professionals, and patent authorization per ten thousand people. Government financial assistance covers the share of technological spending in the overall government expenditure, and the proportion of educational expenditure in total government expenditure. The data processing process is similar with EP through standardized method.

Control variables

The relative research confirms that the regional economic advancement standard, industrial structure, openness, population density (PD) and energy consumption intensity (EC) all affect the regional EP. Hence, this study selects five variables as control variables to limit estimation errors.[110] The first variable is ED. Following standard practice,[106] the natural logarithm of provincial Gross Domestic Product (GDP) per capita is utilized as indicator for presenting ED. The second variable is PD. Total population divided by the total area in square kilometers is adopted to measure this index.[111] The third variable is EC. The measure of EC is the ratio of provincial electricity consumption to regional GDP.[112] The fourth variable is FDI. It is represented by the natural logarithm of the exact use of FDI.[113] The fifth variable is rationalization of industrial

Table 1. Descriptive statistical results of panel data for each variable

Variables	Observations	Mean	Standard deviation	Min	Max
EP	403	0.301	0.186	0.000	0.728
HI	403	0.149	0.102	0.063	0.839
ED	403	10.673	0.532	9.147	12.013
PD	403	5.314	1.496	0.866	8.281
RIS	403	0.516	0.311	−0.098	1.361
FDI	403	5.103	1.906	−1.220	7.495
EC	403	0.108	0.073	0.031	0.409
ET	403	1.348	1.154	0.000	5.546
ER	403	1.283	0.605	0.271	3.884

structure level (RIS). Referring to Hu et al.,[29] we construct the following formula $RIS = \sum_{i=1}^{n} \left(\frac{Y_i}{Y}\right) ln\left(\frac{\frac{Yi}{Li}}{\frac{Y}{L}}\right)$, where Y reflects the real output values, L shows employment level, i denotes the industry, and n indicates the amount of sector.

Mediating variable

In this research paper, ET is identified as the mediating variable. Conforming to the research conducted by Bhupendra and Sangle[114] and Wang et al.,[99] ET is assessed through regional thermal power generation data. Currently, thermal power generation remains the predominant source of electricity in China. Statistics suggest that coal-fired electricity continued to dominate, representing 70.5% of the total in 2017.[99] Moreover, the primary energy source for thermal power generation is predominantly coal, characterized by low conversion efficiency and significant pollution levels. These factors contribute to substantial environmental damage, as highlighted in the research by Fang et al.[115] The heavy reliance on coal in thermal power generation poses challenges for sustainable energy practices and environmental conservation efforts in China.[116]

Moderating variable

Our study selects the ER as moderating variable. As for ER, scholars have measured it from different angles such as ER policies, environmental governance investment, pollution emissions, and environmental governance performance.[117] However, these indicators can only reflect the level of ER from a certain side but cannot reflect the comprehensive level of it. Drawing on the practice of Wu et al.,[118] the ratio of regional GDP to whole regional energy utilization is used to reflect the intensity of ER, which can reflect the comprehensive effect of regional ER. The larger the ratio means that the more obvious the efficiency of ER on energy conservation and emission decrease is at a certain level of GDP. It also indicates that the intensity ER it is greater.

Preliminary analysis

Our study selects the panel data from 2008 to 2020 of 31 China's provincial-level administrative regions. The original data can be obtained from the National Bureau of Statistics, *China Statistical Yearbook*, *China Energy Statistical Yearbook* and *China Environmental Yearbook*. The HI index and the EP index have eliminated dimensional considerations.[119] In addition, the data of the relevant control variables are logarithmically processed.[120]

In Table 1, the mean value of EP keeps 0.301, reflecting that the EP situation is still high. Being confronted with serious EP, China has taken active policies, such as New Environmental Protection Law, but the environmental issues remain severe. Yale University published The Global Environmental Performance Index (EPI) Report (2020), China's EPI score dropped from 60.74 in 2018 to 37.3 in 2020, ranking 120th among 180 participating countries and regions.[93] The standard deviation of EP is 0.186, which is reversely huge, showing that there are great differences among different regions. Moreover, the mean value of HI is 0.149, which reflects that China's innovation abilities should be to move forward a single step, and its standard deviation of 0.102 remains reversely high, showing that there are distinct differences in HI in various districts.

Benchmark regression results

This study first employs the benchmark panel econometric model to verify the linear impact of HI on EP in China's 31 provincial-level administrative regions. Based on Hausman test results, we adopt the fixed-effects model. We conduct stepwise regression analysis by gradually introducing control variables to overcome potential omitted variables bias. Table 2 presents the findings for Equation 5. Columns (1)–(6) in Table 2 show the estimated findings with control variables systematically added. The coefficients of HI in each column are negative and statistically significant, demonstrating that HI is beneficial for reducing EP. The results are consistent with Chen et al.[121] and support hypothesis 1. In China, the average annual growth rate of high-tech patents granted exceeded 20% between 2012 and 2020.[122] Therefore, increasing HI is beneficial for developing pollution control technologies as well as optimizing energy consumption and industrial structure.[123] It is

Table 2. Benchmark regression results

Variables	(1)	(2)	(3)	(4)	(5)	(6)
HI	−0.390*** (−4.10)	−0.415*** (−4.37)	−0.366*** (−3.86)	−0.366*** (−3.86)	−0.300*** (−3.08)	−0.288*** (−2.99)
ED		0.056*** (2.61)	0.069*** (3.24)	0.069*** (3.24)	0.084*** (3.83)	0.097*** (4.36)
PD			0.140*** (2.09)	0.140** (2.09)	0.150*** (2.26)	0.176*** (2.65)
RIS				0.003*** (2.98)	0.033*** (3.24)	0.029*** (2.76)
FDI					−0.013*** (2.63)	−0.015*** (−2.99)
EC						0.376*** (2.64)
Constant	0.374*** (27.16)	−0.182 (−0.85)	0.396 (1.06)	0.396 (1.06)	0.355 (0.96)	0.326 (0.88)
Province	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
R^2	0.198	0.213	0.243	0.243	0.258	0.274
Obs	403	403	403	403	403	403

Note: *** and ** indicate significance at 1% and 5% levels, respectively.

estimated that non-fossil energy consumption and natural gas will account for a combined 35% of total energy consumption, which is expected to reduce EP.

In terms of control variables, ED's coefficient is considerably positive, demonstrating that environmental quality shows signs of continuous deterioration in the process of pursuing increased regional per capita GDP. In general, economic growth tends to raise energy consumption, particularly fossil fuels, which inevitably increases pollution emissions.[124] The coefficient of PD is positive, demonstrating that increased PD worsens environmental quality. Higher PD increases transportation use (i.e., cars and planes) and raises household incomes, which stimulates energy consumption and EP.[125] The coefficient of RIS is also positive, indicating that secondary and tertiary industry development remains unbalanced in most areas of China, which has a considerable influence on regional EP. From 1978 to 2019, China's production of major industrial products grew rapidly. For example, steel and automobile products maintained 10.2% and 13.4% annual growth rates, respectively.[1] In other words, China's industrialization is still undergoing development, with a negative influence on the environment.

Furthermore, the coefficient of the degree of opening to FDI is significantly negative. For every 1% increase, EP is reduced by 0.015%. This indicates that the entry of foreign capital introduces progressive management experience, technologies, and environmental protection standards that are beneficial for reducing EP.[126] China's average annual FDI since 2001 is US$ 55.24 billion, and has started to flow into capital intensive industries such as high-tech and high-end equipment, providing technological support for addressing environmental issues.[127] Finally, the coefficient of EC is positive, indicating that 1% growth in national EC will result in a 0.376% increase in EP. The finding indicates that EC growth will have a negative effect on environmental quality and further aggravate EP. China generated 7,779.06 billion kWh of electricity in 2020, with 5,330.25 billion kWh coming from thermal energy production, representing 68.5% of total generation.[81] The high share of thermal power generation directly emits an enormous quantity of pollutants such as CO_2 and SO_2, with an extremely negative effect on the environment.

Endogeneity must be addressed because the outcomes in Table 2 indicate an obviously negative connection between HI and EP. First, the model may be affected by stochastic bias resulting from a nonrandom sample.[128] Second, the model could possibly omit relevant variables as it is difficult to identify all decisive factors. Hence, we next examine how to solve potential endogeneity issues. The universally employed approach is to identify an effective instrumental variable (IV) to overcome the endogenous issues in the overall model. The IV should not have a direct impact on EP but should be linked to HI in China. Due to data limitations and the potential difficulty of exploring variables that can be used as effective IVs, we used the lagged phase of HI (LHI) as an IV. Table 3 shows the regression results after solving the

Table 3. Test of endogeneity

Variables	(1)
LHI	−0.281*** (−2.87)
Control variables	YES
Constant	0.166 (0.46)
Province	YES
Year	YES
R2	0.309
Obs	403

Note: *** indicate significance at 1% level.

Table 4. Results of bootstrap mediation regression analysis

Mediator	Effect	Obs coef.	Bootstrap std. err	P> | Z |	[95% Conf. interval]
ET	Direct	−0.309	0.072	0	[-0.452, −0.168]
	Indirect	−0.599	0.068	0	[-0.731, −0.466]

endogeneity problem. When we lag the core explanatory variable by one period, the regression results confirm our expectations. The results reveal that EP decreases by 0.281% when LHI increases by 1%, indicating that the IVs are effective.

Mechanism test

Hypotheses 1 can be effectively assumed based on the evidence above; however, the mechanism through which HI influences EP requires further investigation. In the aforementioned discussion, this study identified the mechanism of ET through which HI affects EP. HI is beneficial to more enterprises, particularly those in the secondary industry, increases resource efficiency, and promotes the application of renewable energy sources instead of traditional fossil fuels to reduce EP. The outcomes of bootstrap analysis of the mediating effect are reflected in Table 4, revealing a significant mediating effect. According to the confidence intervals corresponding to the indirect effect, all mediators exclude zero, verifying that HI can reduce EP through energy structure adjustment. Further testing the weight of the mediating effect reveals that a total effect coefficient of − 0.908, the direct effect coefficient was −0.309, and the mediating effect coefficient was −0.599. Through calculation, the mediating effect accounted for 65.9%, indicating that HI is beneficial for reducing EP by promoting ET. For instance, China launched *The Action Plan for Energy Development Strategy*, which aims to develop renewable energy and achieve ET. In 2019, China's total power generation from renewable sources was 732.3 GWh, representing 26.1% of the global total, and the average annual rate exceeds 126.47%.[129] Therefore, hypothesis 2 is validated.

To further consider how HI affects EP under ER, we add an interaction term between ER and HI based on the benchmark regression and the result is reflected in Table 5. The coefficient of the interaction term is 0.201; thus, the final coefficient of HI is −0.43 (−0.631 + 0.201). This means that ER weakens the function of HI in reducing EP. The rationale for this pattern is that as ER becomes stricter, the costs of compliance rise,[130] which takes away money from R&D investments. Furthermore, investment in pollution reduction initiatives does not yield immediate profit, which can deter managers from making green innovation investments because short-term profit is prioritized over long-term sustainable practices. Unfortunately, the low return on investment from innovation often has a negative knock-on effect on product quality and quantity. Consequently, companies are hesitant to take risks on innovation and instead opt for more traditional, cheaper approaches to production, even when they are environmentally harmful. Hypothesis 3 is verified.

Heterogeneity analysis

The estimates in the previous section support the theory expressed in hypothesis 1 but do not examine the provinces' locations. Due to imbalanced regional development, HI may have heterogeneous effects in different regions. Therefore, we next examine the differences between China's southern and northern regions,[131,132] to explore whether the effect of HI on EP is diverse, presenting the results in Table 6. We conclude that the effectiveness of HI in reducing EP differs significantly between the south and the north. According to column (1) of Table 6,

Table 5. The moderating effect of environmental regulation

Variables	(1)
HI	−0.631** (−2.42)
ER	−0.184*** (−8.46)
ER*HI	0.201*** (4.14)
ED	0.107*** (4.98)
PD	−0.195*** (−3.14)
RIS	0.030*** (3.12)
FDI	−0.006*** (−1.35)
EC	0.253** (2.07)
Constant	0.470 (1.39)
Province	YES
Year	YES
R^2	0.397
Obs	403

Note: *** and ** indicate significance at 1% and 5% levels, respectively.

Table 6. Heterogeneity estimation results

Variables	(1)	(2)
HI	−0.237** (−2.16)	−0.532*** (−2.63)
Control variables	YES	YES
Constant	0.247 (0.43)	−2.107 (−1.36)
Province	YES	YES
Year	YES	YES
R^2	0.969	0.946
Obs	208	195

Note: *** and ** indicate significance at 1% and 5% levels, respectively.

the coefficient of HI in northern provinces is −0.237, with a 5% significance level, while in column (2), the coefficient of HI in southern provinces is −0.532, with a 1% significance level. Therefore, the impact of HI on EP is more effective in the south, based on similar sample sizes.

The rationale for this phenomenon is attributable to the four circumstances. First, from the perspective of innovation subjects, more innovative enterprises have been established in the south than in the north, and this gap is increasing.[133] From 2009 to 2018, the gap between the number of new innovative enterprises in northern and southern China widened from 142,000 to 1.586 million. Second, the growth of innovation input in the north slowed down, and the gap between the north and south considerably widened.[134] From 2009 to 2017, the gap in investment in innovation between the north and south widened from 10.06 billion yuan to 427.16 billion yuan. Third, from 2009 to 2017, the gap between northern and southern universities' graduating undergraduates widened from 137,000 to 324,000, expanding the pool of innovative talent.[135] Fourth, in terms of innovation output, more patent applications are filed in the south than in the north. By 2017, the amount of new patent applications in the south was 2.8 times higher than in the north, marking the peak of China's north–south gap.

China's regional ED has exhibited clear patterns of division, with the south experiencing faster growth and a rising economic share, while the north lags behind, resulting in a shift in the country's economic center of gravity toward the south.[136] The unequal distribution of financial resources across geographical domains highlights the north-south economic divide. The northern region's capacity to allocate financial resources is noticeably inadequate, as seen from the financing size statistics. In 2013, the northern region accounted for 42.8% of the nation's social financing; however, this figure had dropped to 28.3% by 2021. According to Yang and Zhou,[137] the "financial accelerator" approach has contributed to the growing economic imbalance between the north and south due to the unequal distribution of financial resources. Without sufficient financial resources, regions can find it challenging to leverage the multiplier effect of technology investment.[117] Furthermore, regarding industrial structure, private, high-tech businesses in southern China demonstrate impressive dynamism, whereas state-owned, highly polluting enterprises remain crucial in the country's north. Therefore, northern China faces increasing pressure to advance industrial modernization, but provinces lack adequate technological assistance and funding support. In summary, differences in innovation capacity, economic division, financial support, industrial structure, and other factors between the north and south have led to divergent EP control outcomes.

Robustness tests

We next broaden the scope of the explained variables and replace EP with $PM_{2.5}$ ($PM_{2.5}$ refers to particulate matter with diameters that are less than 2.5 μm) particulate matter.[138] $PM_{2.5}$ is a major pollutant, and can also reflect the degree of air pollution.[139] Column (1) of Table 7 shows that the coefficient is −1.087, and is statistically significant at 1% level. The results demonstrate that HI is beneficial for reducing $PM_{2.5}$, which is consistent with our benchmark regression results. China's rapid ED has brought enormous damage to the environment. For example, in 2019,

Table 7. Test of robustness

Variables	(1)	(2)	(3)
HI	−1.087*** (−6.33)		−0.896*** (0.226)
GTI		−0.058*** (−5.21)	
Control variables	YES	YES	YES
Constant	4.656*** (7.10)	0.166 (0.46)	0.172 (0.484)
Province	YES	YES	YES
Year	YES	YES	YES
R^2	0.827	0.309	0.951
Obs	403	403	351

Note: *** indicates significance at 1% level.

Table 8. The regression results for EP*

Variables	(1)
HI*	−0.036** (0.012)
ED	−0.128 (0.198)
PD	−35.950*** (4.145)
RIS*	0.102* (0.039)
FDI	−0.049* (0.024)
EC*	0.292*** (0.031)
Constant	163.160*** (19.633)
Province	YES
Year	YES

Note: ***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively.

the nation's 337 cities experienced 1,666 days of severe pollution, with $PM_{2.5}$ being the primary pollutant on 1,313 of those days.[140] Considering the severe $PM_{2.5}$ pollution, the Chinese government continuously reinforces policies to promote high-quality technology development and adoption, such as *The 14th Five-Year Plan for Technological Innovation in the Ecological Environment Field*. Such initiatives can reduce the use of raw materials and improve environmental quality in addition to enhancing sustainable development and green transition.[141]

We next employ the number of green technology innovation (GTI) patent applications as an alternative independent variable to replace HI.[142] The ecological value of GTI is well known, and can reflect the application of HI in the field of environmental protection. In column (2) of Table 7, we replace the explanatory variable with GTI. The result after replacing the independent variable shows that for every 1% rise in green technology development, EP drops by 0.058%. This confirms that the baseline regression estimates are robust. The 20th Communist Party of China (CPC) National Congress in China highlighted the contribution of GTI to advancing sustainability as a crucial technological backbone for improving development of the highest caliber.[27] Green patents granted in China rose to 31,100 in 2020, and the average annual growth rate has exceeded 20% since 2012.[124] Increasing green technologies strengthens environmental protection, resource conservation, and waste recycling, which is beneficial for the environment.

We next change the sample size to ensure the common function of HI in addressing EP by excluding Beijing, Shanghai, Xizang, and Xinjiang from the original dataset to determine whether the empirical results remain robust after deleting some provinces. The reasons for this choice are that Beijing and Shanghai have the richest educational and research resources in China; therefore, subsequent HI may raise the overall level of innovation. In addition, Xizang and Xinjiang are located in western China, with large land areas and lower populations, indicating less active social activities. In column (3) of Table 7, we re-estimate = Equation 5 with the revised sample. The result shows that the coefficient of HI is −0.896, demonstrating 1% rise in HI development, and EP drops by 0.896%. This finding conforms to the baseline regression results, validating that the estimates are robust. The results also demonstrate the importance of implementing a national strategy to develop science and technology and achieve sustainable development for society, humanity, and the economy.

Further analysis

To conduct comparative analysis, we select BRICS countries as a research sample, excluding Russia due to data availability and war. The remaining countries include Brazil, India, China, and South Africa. As these countries are considered developing countries that face serious EP challenges,[84,143] we examine the relationship between technological innovation and EP for comparison. Due to a lack of data for constructing HI and EP indices for these countries, we use global innovation index and CO_2 per capita to represent HI (HI*) and EP (EP*). These two datasets are obtained from the World Intellectual Property Organization and the World Bank. Considering data availability, we employ the proportion of renewable energy in energy consumption and the proportion of workers in the secondary industry to measure EC (EC*) and RIS (RIS*). Control variables are consistent with the baseline model, including GDP per capita, PD, and FDI.

The corresponding empirical results are presented in Tables 8 and 9, revealing that the coefficients of HI* demonstrate that technological innovation is beneficial for addressing EP. BRICS countries are situated at the end of the global value chain, indicating that ED comes at the cost of sacrificing the environment. Thus, these countries also have to depend on innovation, especially HI, to overcome technological barriers and achieve sustainable development. In detail, governments must promote innovation and R&D efforts in green technologies, formulating and improving policies to guide enterprises to choose appropriate directions for technological advancement through collaboration between science, technology, and industry. Furthermore, countries should enhance regional cooperation and exchange in green and low-carbon technologies; promote technology spillover, diffusion, and transfer; and establish new patterns of mutually promoting GTI.

DISCUSSIONS

This study examines the functional role of HI in addressing EP in China, specifically focusing on ET, ER, and regional heterogeneity. The results provide empirical evidence using the annual data from 2008 to 2020 encompassing 31 provinces in China and employing the 2SLS method. The following five major empirical findings emerge. First, the results confirm the positive role of HI in reducing EP after excluding the influence

Table 9. The regression results for BRICS countries

Variables	
HI	−0.036*** (0.011)
ED	−0.128 (0.198)
PD	−35.950*** (4.145)
RIS	0.102** (0.038)
FDI	−0.049* (0.024)
EC	0.292*** (0.031)
Constant	163.160*** (19.663)
Province	YES
Year	YES

Note: ***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively.

of control variables. Second, the mediating effect of ET is demonstrated, showing that HI increases resource efficiency and non-fossil energy use and accelerates the ET process. Third, ER increases the costs of compliance, which reduces risk preference for HI, causing managers to opt for traditional high pollution processes instead. Fourth, the benchmark regression results remain robust and consistent after changing dependent and independent variables and the estimation regression method. Fifth, regional differences in innovation resource levels reflect various effects of HI on EP, with the south outperforming the north.

Based on the empirical outcomes, we provide the following policy suggestions. First, the positive role of HI in reducing EP implies that the government should establish long-term incentive mechanisms to promote HI and improve supporting systems related to innovation. This can be accomplished by advancing high-quality human resources, strengthening cooperation between universities and scientific research institutes, and providing financial support for developing innovative applications. Second, the mediating effect of ET is confirmed in the empirical analysis, which encourages the government to adopt active energy policies. China not only promotes innovation in decarbonization process of fossil energies, but also endorses technological breakthroughs in non-fossil energies. In addition, some national environmental strategies, such as carbon peak and neutrality must be strategically implemented and dominate the ET process. Third, increased ER intensity weakens the effect of HI on reducing EP. Therefore, reasonable ER policies must be formulated based on the realities of ED, R&D investment, and human capital. Furthermore, incentive-based policies are also needed to reduce compliance costs and make enterprises more focused on HI activities. Fourth, regional differences in the allocation of innovation resources explain the variations in reducing EP caused by HI in China. Local governments must focus on the driving role of innovation in key regions and industries, promote the integrated development of new industries and local traditional business, and advance the efficient allocation and intensive use of industrial ecosphere elements such as talent, capital, and technology.

Limitations of the study

This study uses provincial panel data instead of city-level data due to missing data at the city level. In future analyses, we aim to explore the possibility of replacing the original indicators with new ones and constructing city-level HI and EP indices to re-examine their relationship. In addition, we can also conduct comparative analyses for countries that face similar technological dilemmas and EP by developing national HI and EP indices.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Sun, K., Liu, C., Yang, Z., Han, J., Xie, W., and Cao, Y. (2022). The impact of industrial. structure on the environment pollution and its spatial-temporal differences in Henan, China. J. Clean. Prod. *381*, 135127. https://doi.org/10.1016/j.jclepro.2022.135127.
2. Asif, M.H., Zhongfu, T., Irfan, M., and Işık, C. (2023). Do environmental knowledge and green trust matter for purchase intention of eco-friendly home appliances? An application of extended theory of planned behavior. Environ. Sci. Pollut. Res. Int. *30*, 37762–37774. https://doi.org/10.1007/s11356-022-24899-1.
3. Xu, Y., Wen, S., and Tao, C.Q. (2023). Impact of environmental tax on pollution control: A sustainable development perspective. Econ. Anal. Pol. *79*, 89–106. https://doi.org/10.1016/j.eap.2023.06.006.
4. Qadeer, A., Anis, M., Ajmal, Z., Kirsten, K.L., Usman, M., Khosa, R.R., Liu, M., Jiang, X., and Zhao, X. (2022). Sustainable development goals under threat? Multidimensional impact of COVID-19 on our planet and society outweigh short term global pollution reduction. Sustain. Cities Soc. *83*, 103962. https://doi.org/10.1016/j.scs.2022.103962.
5. Ali, S., Yan, Q., Dilanchiev, A., Irfan, M., and Fahad, S. (2023). Modeling the economic viability and performance of solar home systems: a roadmap towards clean energy for environmental sustainability. Environ. Sci. Pollut. Res. Int. *30*, 30612–30631. https://doi.org/10.1016/j.renene.2020.12.074.
6. Wen, H., Liang, W., and Lee, C.C. (2023). China's progress toward sustainable development in pursuit of carbon neutrality: Regional differences and dynamic evolution. Environ. Impact Assess. Rev. *98*, 106959. https://doi.org/10.1016/j.eiar.2022.106959.
7. Song, C., Wu, Z., Dong, R.K., and Dinçer, H. (2023). Greening south Asia: Investing in sustainability and innovation to preserve natural resources and combat environmental pollution. Resour. Pol. *86*, 104239. https://doi.org/10.1016/j.resourpol.2023.104239.
8. Javan, K., Altaee, A., BaniHashemi, S., Darestani, M., Zhou, J., and Pignatta, G. (2024). A review of interconnected challenges in the water-energy-food nexus: Urban pollution perspective towards sustainable development. Sci. Total Environ. *912*, 169319. https://doi.org/10.1016/j.scitotenv.2023.169319.
9. Ibrahim, R.L. (2022). Post-COP26: can energy consumption, resource dependence, and trade openness promote carbon neutrality? Homogeneous and heterogeneous analyses for G20 countries. Environ. Sci. Pollut. Res. Int. *29*, 86759–86770. https://doi.org/10.1007/s11356-022-21855-x.
10. Ibrahim, R.L. (2022). Beyond COP26: can income level moderate fossil fuels, carbon emissions, and human capital for healthy life expectancy in Africa? Environ. Sci. Pollut. Res. Int. *29*, 87568–87582. https://doi.org/10.1007/s11356-022-21872-w.
11. Ibrahim, R.L., Huang, Y., Mohammed, A., and Adebayo, T.S. (2023). Natural resources-sustainable environment conflicts amidst COP26 resolutions: investigating the role of renewable energy, technology innovations, green finance, and structural change. Int. J. Sustain. Dev. World Ecol. *30*, 445–457. https://doi.org/10.1080/13504509.2022.2162147.
12. Zhan, Y., Lin, B., and Sun, C. (2023). How does pollution heterogeneity affect the role of cleaner production regulations? Evidence from Chinese enterprises' domestic value-added in exports. Energy Econ. *122*, 106681. https://doi.org/10.1016/j.eneco.2023.106681.
13. Huang, X., Liu, W., Zhang, Z., Zou, X., and Li, P. (2023). Quantity or quality: Environmental legislation and corporate green innovations. Ecol. Econ. *204*, 107684. https://doi.org/10.1016/j.ecolecon.2022.107684.
14. Pu, X., Zeng, M., and Zhang, W. (2023). Corporate sustainable development driven by high-quality innovation: Does fiscal decentralization really matter? Econ. Anal. Pol. *78*, 273–289. https://doi.org/10.1016/j.eap.2023.03.008.
15. Zhou, B., Zeng, X., Jiang, L., and Xue, B. (2020). High-quality Economic Growth under the Influence of Technological Innovation Preference in China: A Numerical Simulation from the Government Financial Perspective. Struct. Change Econ. Dynam. *54*, 163–172. https://doi.org/10.1016/j.strueco.2020.04.010.
16. Xu, R., Yao, D., and Zhou, M. (2023). Does the development of digital inclusive finance improve the enthusiasm and quality of corporate green technology innovation? J. Innov. Knowl. *8*, 100382. https://doi.org/10.1016/j.jik.2023.100382.
17. Li, Z., and Mao, J. (2019). Local Governments' Tax Competition, Industrial Structure Adjustment and Regional Green Development in China. China Financ. Econ. Rev. *8*, 93–111. https://doi.org/10.1515/cfer-2019-080106.
18. Du, G., Zhou, C., and Ma, Y. (2023). Impact mechanism of environmental protection tax policy on enterprises' green technology innovation with quantity and quality from the micro-enterprise perspective. Environ. Sci. Pollut. Res. Int. *30*, 80713–80731. https://doi.org/10.1007/s11356-023-28109-4.
19. Zhang, S., Xie, W., Sun, S., Wu, F., and Xue, Y. (2024). Nexus of green energy innovation, governance quality, and CO2 emissions in natural resource sector: The role of sustainable human development. Resour. Pol. *88*, 104493. https://doi.org/10.1016/j.resourpol.2023.104493.
20. Bai, D., Hu, J., Irfan, M., and Hu, M. (2023). Unleashing the impact of ecological civilization pilot policies on green technology innovation: Evidence from a novel SC-DID model. Energy Econ. *125*, 106813. https://doi.org/10.1016/j.eneco.2023.106813.
21. Deng, Z., Song, S., Jiang, N., and Pang, R. (2023). Sustainable development in China? A nonparametric decomposition of economic growth. China Econ. Rev. *81*, 102041. https://doi.org/10.1016/j.chieco.2023.102041.
22. Gao, Z., Li, L., and Hao, Y. (2024). Resource industry dependence and high-quality economic development of Chinese style: Reexamining the effect of the "Resource Curse". Struct. Change Econ. Dynam. *68*, 1–16. https://doi.org/10.1016/j.strueco.2023.09.013.
23. Tang, C., Rosland, A., Yasmeen, R., and Long, Y. (2023). The threshold analysis of economic growth, FDI and trade on environment pollution in China using provincial panel data. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-023-03670-7.
24. Zhang, Y., Sun, Z., and Zhou, Y. (2023). Green merger and acquisition and green technology innovation: Stimulating quantity or quality? Environ. Impact Assess. Rev. *103*, 107265. https://doi.org/10.1016/j.eiar.2023.107265.
25. Cheng, Z., Xu, Q., and Sanderson, I.F. (2021). China's economic growth and haze pollution control. Nat. Hazards *107*, 2653–2669. https://doi.org/10.1007/s11069-021-04565-4.

26. Wang, X., and Luo, Y. (2020). Has technological innovation capability addressed environmental pollution from the dual perspective of FDI quantity and quality? Evidence from China. J. Clean. Prod. *258*, 120941. https://doi.org/10.1016/j.jclepro.2020.120941.
27. Zhang, D., Narbaev, T., Cheng, J., and Aliyeva, A. (2023). How natural resources collaboration affects the pollutants level and economic growth: Novel evidence from China. Resour. Pol. *85*, 103801. https://doi.org/10.1016/j.resourpol.2023.103801.
28. Sun, Y., Razzaq, A., Sun, H., and Irfan, M. (2022). The asymmetric influence of renewable energy and green innovation on carbon neutrality in China: Analysis from non-linear ARDL model. Renew. Energy *193*, 334–343. https://doi.org/10.1016/j.renene.2022.04.159.
29. Hu, L., Yuan, W., Jiang, J., Ma, T., and Zhu, S. (2023). Asymmetric effects of industrial structure rationalization on carbon emissions: Evidence from thirty Chinese provinces. J. Clean. Prod. *428*, 139347. https://doi.org/10.1016/j.jclepro.2023.139347.
30. Lin, Z., and Liao, X. (2023). Synergistic effect of energy and industrial structures on carbon emissions in China. J. Environ. Manag. *345*, 118831. https://doi.org/10.1016/j.jenvman.2023.118831.
31. Asif, M.H., Zhongfu, T., Ahmad, B., Irfan, M., Razzaq, A., and Ameer, W. (2023). Influencing factors of consumers' buying intention of solar energy: a structural equation modeling approach. Environ. Sci. Pollut. Res. Int. *30*, 30017–30032. https://doi.org/10.1007/s11356-022-24286-w.
32. Li, Q., Wang, Y., Chen, W., Li, M., and Fang, X. (2021). Does improvement of industrial land use efficiency reduce PM2.5 pollution? Evidence from a spatiotemporal analysis of China. Ecol. Indicat. *132*, 108333. https://doi.org/10.1016/j.ecolind.2021.108333.
33. Mughal, N., Arif, A., Jain, V., Chupradit, S., Shabbir, M.S., Ramos-Meza, C.S., and Zhanbayev, R. (2022). The role of technological innovation in environmental pollution, energy consumption and sustainable economic growth: Evidence from South Asian economies. Energy Strategy Rev. *39*, 100745. https://doi.org/10.1016/j.esr.2021.100745.
34. Hou, S., Yu, K., and Fei, R. (2023). How does environmental regulation affect carbon productivity? The role of green technology progress and pollution transfer. J. Environ. Manag. *345*, 118587. https://doi.org/10.1016/j.jenvman.2023.118587.
35. Gebreegziabher, Z., Van Kooten, G.C., and Van Soest, D.P. (2017). Technological innovation and dispersion: Environmental benefits and the adoption of improved biomass cookstoves in Tigrai, northern Ethiopia. Energy Econ. *67*, 337–345. https://doi.org/10.1016/j.eneco.2017.08.030.
36. Danish, and Ulucak, R. (2021). Renewable energy, technological innovation and the environment: A novel dynamic auto-regressive distributive lag simulation. Renew. Sustain. Energy Rev. *150*, 111433. https://doi.org/10.1016/j.rser.2021.111433.
37. Zhang, L., Mu, R., Hu, S., Yu, J., and Zhang, J. (2022). Industrial coagglomeration, technological innovation, and environmental pollution in China: Life-cycle perspective of coagglomeration. J. Clean. Prod. *362*, 132280. https://doi.org/10.1016/j.jclepro.2022.132280.
38. Liao, H., Chen, Y., Tan, R., Chen, Y., Wei, X., and Yang, H. (2023). Can natural resource rent, technological innovation, renewable energy, and financial development ease China's environmental pollution burden? New evidence from the nonlinear-autoregressive distributive lag model. Resour. Pol. *84*, 103760. https://doi.org/10.1016/j.resourpol.2023.103760.
39. Rong, Z., Zhang, F., and Chen, S. (2023). Short-term loans and Firms' high-quality innovation: Evidence from the access to patent-backed loans in China. Rev. *78*, 101918. https://doi.org/10.1016/j.chieco.2023.101918.
40. Hossain, M.E., Rej, S., Hossain, M.R., Bandyopadhyay, A., Tama, R.A.Z., and Ullah, A. (2023). Energy mix with technological innovation to abate carbon emission: fresh evidence from Mexico applying wavelet tools and spectral causality. Environ. Sci. Pollut. Res. Int. *30*, 5825–5846. https://doi.org/10.1007/s11356-022-22555-2.
41. Chen, Y., and Liu, Y. (2021). How biased technological progress sustainably improve the energy efficiency: An empirical research of manufacturing industry in China. Energy *230*, 120823. https://doi.org/10.1016/j.energy.2021.120823.
42. Zhang, D., Zhao, M., Wang, Y., Vigne, S.A., and Benkraiem, R. (2024). Technological innovation and its influence on energy risk management: Unpacking China's energy consumption structure optimisation amidst climate change. Energy Econ. *131*, 107321. https://doi.org/10.1016/j.eneco.2024.107321.
43. Higham, K., de Rassenfosse, G., and Jaffe, A.B. (2021). Patent Quality: Towards a Systematic Framework for Analysis and Measurement. Res. Pol. *50*, 104215. https://doi.org/10.1016/j.respol.2021.104215.
44. Zhao, S., Zeng, D., Li, J., Feng, K., and Wang, Y. (2023). Quantity or quality: The roles of technology and science convergence on firm innovation performance. Technovation *126*, 102790. https://doi.org/10.1016/j.technovation.2023.102790.
45. Dang, J., and Motohashi, K. (2015). Patent statistics: a good indicator for innovation in China? Patent subsidy program impacts on patent quality. China Econ. Rev. *35*, 137–155. https://doi.org/10.1016/j.chieco.2015.03.012.
46. Feng, W., and Li, J. (2021). International technology spillovers and innovation quality: Evidence from China. Econ. Anal. Pol. *72*, 289–308. https://doi.org/10.1016/j.eap.2021.09.003.
47. Duan, Y., Yang, M., Huang, L., Chin, T., Fiano, F., de Nuccio, E., and Zhou, L. (2022). Unveiling the impacts of explicit vs. tacit knowledge hiding on innovation quality: The moderating role of knowledge flow within a firm. J. Bus. Res. *139*, 1489–1500. https://doi.org/10.1016/j.jbusres.2021.10.068.
48. Wang, X., Liu, S., Tao, Z., and Cao, Q. (2022). The impact of industrial policy and its combinations on the innovation quality of wind power enterprises: A study from the perspective of financing modes. Renew. Energy *188*, 945–956. https://doi.org/10.1016/j.renene.2022.02.057.
49. Huang, H., Mbanyele, W., Wang, F., Song, M., and Wang, Y. (2022). Climbing the quality ladder of green innovation: Does green finance matter? Technol. Forecast. Soc. Change *184*, 122007. https://doi.org/10.1016/j.techfore.2022.122007.
50. Zhu, Y., Gao, H., Hu, Y., Ding, Q., and Tang, Y. (2023). Can local environmental constraints improve enterprise's green innovation quality? Evidence from Chinese-listed firms? Environ. Sci. Pollut. Res. Int. *30*, 389–406. https://doi.org/10.1007/s11356-022-22161-2.
51. Zheng, Z., Han, X., and Xiao, Y. (2023). Quantity or quality? Regional innovation policy and green technology innovation. Environ. Sci. Pollut. Res. Int. *30*, 77358–77370. https://doi.org/10.1007/s11356-023-27341-2.
52. Han, F., and Mao, X. (2023). Impact of intelligent transformation on the green innovation quality of Chinese enterprises: evidence from corporate green patent citation data. Appl. Econ. 1–18. https://doi.org/10.1080/00036846.2023.2244256.
53. Asif, M.H., Zhongfu, T., Dilanchiev, A., Irfan, M., Eyvazov, E., and Ahmad, B. (2023). Determining the influencing factors of consumers' attitude toward renewable energy adoption in developing countries: a roadmap toward environmental sustainability and green energy technologies. Environ. Sci. Pollut. Res. Int. *30*, 47861–47872. https://doi.org/10.1007/s11356-023-25662-w.
54. Ali, M., Irfan, M., Ozturk, I., and Rauf, A. (2023). Modeling public acceptance of renewable energy deployment: a pathway towards green revolution. Economic Ekon. Istraz. *36*, 2159849. https://doi.org/10.1080/1331677X.2022.2159849.
55. Erdogan, S. (2021). Dynamic Nexus between Technological Innovation and Building Sector Carbon Emissions in the BRICS Countries. J. Environ. Manag. *293*, 112780. https://doi.org/10.1016/j.jenvman.2021.112780.
56. Ma, X., Arif, A., Kaur, P., Jain, V., Refiana Said, L., and Mughal, N. (2022). Revealing the effectiveness of technological innovation shocks on CO2 emissions in BRICS: emerging challenges and implications. Environ. Sci. Pollut. Res. Int. *29*, 47373–47381. https://doi.org/10.1007/s11356-022-19053-w.
57. Rej, S., Bandyopadhyay, A., Das, N., Hossain, M.E., Islam, M.S., Bera, P., and Yeedibalii, T. (2023). The asymmetric influence of environmental-related technological innovation on climate change mitigation: what role do FDI and renewable energy play? Environ. Sci. Pollut. Res. Int. *30*, 14916–14931. https://doi.org/10.1007/511356-022-23182-7.
58. Hossain, M.E., Islam, M.S., Bandyopadhyay, A., Awan, A., Hossain, M.R., and Rej, S. (2022). Mexico at the crossroads of natural resource dependence and COP26 pledge: Does technological innovation help? Resour. Pol. *77*, 102710. https://doi.org/10.1016/j.resourpol.2022.102710.
59. Hossain, M.R., Rana, M.J., Saha, S.M., Haseeb, M., Islam, M.S., Amin, M.R., and Hossain, M.E. (2023). Role of energy mix and eco-innovation in achieving environmental sustainability in the USA using the dynamic ARDL approach: Accounting the supply side of the ecosystem. Renew. Energy *215*, 118925. https://doi.org/10.1016/j.renene.2023.118925.

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60. Chen, J., Huang, S., and Ajaz, T. (2022). Natural resources management and technological innovation under EKC framework: A glimmer of hope for sustainable environment in newly industrialized countries. Resour. Pol. *79*, 103016. https://doi.org/10.1016/j.resourpol.2022.103016.
61. Santra, S. (2020). The effect of technological innovation on production-based energy and CO2 emission productivity: evidence from BRICS countries. Afr. J. Sci. Technol. Innov. Dev. *9*, 4–13. https://doi.org/10.1201/9781003008774-2.
62. Dauda, L., Long, X., Mensah, C.N., and Salman, M. (2019). The effects of economic growth and innovation on CO2 emissions in different regions. Environ. Sci. Pollut. Res. Int. *26*, 15028–15038. https://doi.org/10.1007/s11356-019-04891-y.
63. Töbelmann, D., and Wendler, T. (2020). The impact of environmental innovation on carbon dioxide emissions. J. Clean. Prod. *244*, 118787. https://doi.org/10.1016/j.jclepro.2019.118787.
64. Gao, J., Murshed, M., Ghardallou, W., Bakkar Siddik, A., Ali, H., and Khudoykulov, K. (2023). Juxtaposing the environmental consequences of different environment related technological innovations: The significance of establishing good democratic governance. Gondwana Res. *121*, 486–498. https://doi.org/10.1016/j.gr.2023.05.017.
65. Das, N., Gangopadhyay, P., Alam, M.M., Mahmood, H., Bera, P., Khudoykulov, K., Dey, L., and Hossain, M.E. (2023). Does greenwashing obstruct sustainable environmental technologies and green financing from promoting environmental sustainability? Analytical evidence from the Indian economy. Sustain. Dev. *32*, 1069–1080. https://doi.org/10.1002/sd.2722.
66. Aytun, C., Erdogan, S., Pata, U.K., and Cengiz, O. (2024). Associating environmental quality, human capital, financial development and technological innovation in 19 middle-income countries: A disaggregated ecological footprint approach. Technol. Soc. *76*, 102445. https://doi.org/10.1016/j.techsoc.2023.102445.
67. Ahmad, N., Youjin, L., Žiković, S., and Belyaeva, Z. (2023). The effects of technological innovation on sustainable development and environmental degradation: Evidence from China. Technol. Soc. *72*, 102184. https://doi.org/10.1016/j.techsoc.2022.102184.
68. Liang, R., Wen, X., and Zhu, S. (2023). The impact of emission charges on the quality of corporate innovation: Based on the perspective of breakthrough technological innovation. J. Clean. Prod. *404*, 136830. https://doi.org/10.1016/j.jclepro.2023.136830.
69. Hasan, M.M., and Du, F. (2023). Nexus between green financial development, green technological innovation and environmental regulation in China. Renew. Energy *204*, 218–228. https://doi.org/10.1016/j.renene.2022.12.095.
70. Zhao, X., Long, L., Yin, S., and Zhou, Y. (2023). How technological innovation influences carbon emission efficiency for sustainable development? Evidence from China. Resour. Environ. Sustain. *14*, 100135. https://doi.org/10.1016/j.resenv.2023.100135.
71. Zhu, Y., Wang, Z., Yang, J., and Zhu, L. (2020). Does renewable energy technological innovation control China's air pollution? A spatial analysis. J. Clean. Prod. *250*, 119515. https://doi.org/10.1016/j.jclepro.2019.119515.
72. Khattak, S.I., Ahmad, M., Khan, Z.U., and Khan, A. (2020). Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. Environ. Sci. Pollut. Res. Int. *27*, 13866–13881. https://doi.org/10.1007/s11356-020-07876-4.
73. Ke, H., Dai, S., and Yu, H. (2022). Effect of green innovation efficiency on ecological footprint in 283 Chinese Cities from 2008 to 2018. Environ. Dev. Sustain. *24*, 2841–2860. https://doi.org/10.1007/s10668-021-01556-0.
74. Quan, Z., Xu, X., Wang, W., Jiang, J., and Gao, S. (2024). Do industrial solid waste recycling and technological innovation promote low-carbon development in China? New insights from NARDL approach. Sci. Total Environ. *916*, 170446. https://doi.org/10.1016/j.scitotenv.2024.170446.
75. Khezri, M., and Muhamad, G.M. (2023). Environmental effects of entrepreneurship indices on ecological footprint of croplands and grazing lands in the economy. J. Clean. Prod. *414*, 137550. https://doi.org/10.1016/j.jclepro.2023.137550.
76. Karmaker, S.C., Barai, M.K., Sen, K.K., and Saha, B.B. (2023). Effects of remittances on renewable energy consumption: Evidence from instrumental variable estimation with panel data. Util. Pol. *83*, 101614. https://doi.org/10.1016/j.jup.2023.101614.
77. Martin, S., Claxton, K., Lomas, J., and Longo, F. (2023). The impact of different types of NHS expenditure on health: Marginal cost per QALY estimates for England for 2016/17. Health Pol. *132*, 104800. https://doi.org/10.1016/j.healthpol.2023.104800.
78. Lee, C.C., Lu, M., Wang, C.W., and Cheng, C.Y. (2024). ESG engagement, country-level political risk and bank liquidity creation. Pac. Basin Finance J. *83*, 102260. https://doi.org/10.1016/j.pacfin.2024.102260.
79. Chanthawong, A., Dhakal, S., and Jongwanich, J. (2016). Supply and demand of biofuels in the fuel market of Thailand: Two stage least square and three least square approaches. Energy *114*, 431–443. https://doi.org/10.1016/j.energy.2016.08.006.
80. Nasir, M.H., and Zhang, S. (2024). Evaluating innovative factors of the global innovation index: A panel data approach. Innov. Green Dev. *3*, 100096. https://doi.org/10.1016/j.igd.2023.100096.
81. Wang, Q., Hu, A., and Tian, Z. (2022). Digital transformation and electricity consumption: Evidence from the Broadband China pilot policy. Energy Econ. *115*, 106346. https://doi.org/10.1016/j.eneco.2022.106346.
82. Liu, X. (2023). The impact of China's high-quality development of energy on carbon neutrality. Energy Rep. *9*, 2665–2675. https://doi.org/10.1016/j.egyr.2023.01.089.
83. Li, W., Padmanabhan, P., and Huang, C.H. (2024). Directors' & Officers' liability insurance and financing decisions: Evidence from debt structure choice. Pac. Basin Finance J. *83*, 102248. https://doi.org/10.1016/j.pacfin.2023.102248.
84. Zhao, Y., Wang, W., Liang, Z., and Luo, P. (2024). Racing towards zero carbon: Unraveling the interplay between natural resource rents, green innovation, geopolitical risk and environmental pollution in BRICS countries. Resour. Pol. *88*, 104379. https://doi.org/10.1016/j.resourpol.2023.104379.
85. Sun, G., Fang, J., Li, T., and Ai, Y. (2024). Effects of climate policy uncertainty on green innovation in Chinese enterprises. Int. Rev. Financ. Anal. *91*, 102960. https://doi.org/10.1016/j.irfa.2023.102960.
86. Winton, D.J., Anderson, L.G., Rocliffe, S., and Loiselle, S. (2020). Macroplastic pollution in freshwater environments: Focusing public and policy action. Sci. Total Environ. *704*, 135242. https://doi.org/10.1016/j.scitotenv.2019.135242.
87. Liu, P., Zhu, B., and Yang, M. (2021). Has marine technology innovation promoted the high-quality development of the marine economy? -Evidence from coastal regions in China. Ocean Coast Manag. *209*, 105695. https://doi.org/10.1016/j.ocecoaman.2021.105695.
88. O'Shea, F.T., Cundy, A.B., and Spencer, K.L. (2018). The contaminant legacy from historic coastal landfills and their potential as sources of diffuse pollution. Mar. Pollut. Bull. *128*, 446–455. https://doi.org/10.1016/j.marpolbul.2017.12.047.
89. Xiao, W., Kong, H., Shi, L., Boamah, V., and Tang, D. (2022). The Impact of Innovation-Driven Strategy on High-Quality Economic Development: Evidence from China. Sustainability *14*, 4212. https://doi.org/10.3390/su14074212.
90. Ahn, S.J., and Yoon, H.Y. (2020). 'Green chasm' in clean-tech for air pollution: Patent evidence of a long innovation cycle and a technological level gap. J. Clean. Prod. *272*, 122726. https://doi.org/10.1016/j.jclepro.2020.122726.
91. Donis, S., Gómez, J., and Salazar, I. (2023). Economic complexity, property rights and the judicial system as drivers of eco-innovations: An analysis of OECD countries. Technovation *128*, 102868. https://doi.org/10.1016/j.technovation.2023.102868.
92. Kenneth David, L., Wang, J., Angel, V., and Luo, M. (2024). Environmental commitments and Innovation in China's corporate landscape: An analysis of ESG governance strategies. J. Environ. Manag. *349*, 119529. https://doi.org/10.1016/j.jenvman.2023.119529.
93. Yu, A., Zhang, Q., Yu, R., and Cheng, Y. (2023). More is better or in waste? A resource allocation measure of government grants for facilitating firm innovations. Technol. Forecast. Soc. Change *197*, 122918. https://doi.org/10.1016/j.techfore.2023.122918.
94. Luan, F., Yang, X., Chen, Y., and Regis, P.J. (2022). Industrial robots and air environment: A moderated mediation model of population density and energy consumption. Sustain. Prod. Consum. *30*, 870–888. https://doi.org/10.1016/j.spc.2022.01.015.
95. Yang, G., Zhang, G., Cao, D., Zha, D., Gao, X., and Su, B. (2024). China's provincial-level sustainable energy transition requires accelerating renewable energy technological innovation. Energy *288*, 129672. https://doi.org/10.1016/j.energy.2023.129672.
96. Li, X., Zeng, Z., Zhang, Z., Yao, Y., and Du, H. (2023). The rising North-South carbon flows within China from 2012 to 2017. Struct.

Change Econ. Dynam. *64*, 263–272. https://doi.org/10.1016/j.strueco.2023.01.002.

97. Chen, M., Su, Y., Piao, Z., Zhu, J., and Yue, X. (2023). The green innovation effect of urban energy saving construction: A quasi-natural experiment from new energy demonstration city policy. J. Clean. Prod. *428*, 139392. https://doi.org/10.1016/j.jclepro.2023.139392.
98. Bozatli, O., and Akca, H. (2023). The effects of environmental taxes, renewable energy consumption and environmental technology on the ecological footprint: Evidence from advanced panel data analysis. J. Environ. Manag. *345*, 118857. https://doi.org/10.1016/j.jenvman.2023.118857.
99. Wang, J., Song, C., and Yuan, R. (2021). CO_2 emissions from electricity generation in China during 1997-2040: The roles of energy transition and thermal power generation efficiency. Sci. Total Environ. *773*, 145026. https://doi.org/10.1016/j.scitotenv.2021.145026.
100. Meng, Z., Xiong, H., Zhu, C., and Xu, G. (2024). Study on the process technology of energy saving and consumption reducing for municipal sludge-based biochar. Renew. Energy *220*, 119606. https://doi.org/10.1016/j.renene.2023.119606.
101. Yuan, B., and Xiang, Q. (2018). Environmental regulation, industrial innovation and green development of Chinese manufacturing: Based on an extended CDM model. J. Clean. Prod. *176*, 895–908. https://doi.org/10.1016/j.jclepro.2017.12.034.
102. Albrizio, S., Kozluk, T., and Zipperer, V. (2017). Environmental policies and productivity growth: Evidence across industries and firms. J. Environ. Econ. Manag. *81*, 209–226. https://doi.org/10.1016/j.jeem.2016.06.002.
103. Han, L., Xiao, Z., and Yu, Y. (2024). Environmental judicature and enterprises' green technology innovation: A revisit of the porter hypothesis. J. Asian Econ. *91*, 101693. https://doi.org/10.1016/j.asieco.2023.101693.
104. Ouyang, X., Li, Q., and Du, K. (2020). How does environmental regulation promote technological innovations in the industrial sector? Evidence from Chinese provincial panel data. Energy Pol. *139*, 111310. https://doi.org/10.1016/j.enpol.2020.111310.
105. Zhou, K., Luo, H., and Qu, Z. (2023). What can the environmental rule of law do for environmental innovation? Evidence from environmental tribunals in China. Technol. Forecast. Soc. Change *189*, 122377. https://doi.org/10.1016/j.techfore.2023.122377.
106. Zhao, J., Zhao, Z., and Zhang, H. (2021). The impact of growth, energy and financial development on environmental pollution in China: new evidence from a spatial econometric analysis. Energy Econ. *93*, 104506. https://doi.org/10.1016/j.eneco.2019.104506.
107. Ren, S., Du, M., Bu, W., and Lin, T. (2023). Assessing the impact of economic growth target constraints on environmental pollution: Does environmental decentralization matter? J. Environ. Manag. *336*, 117618. https://doi.org/10.1016/j.jenvman.2023.117618.
108. He, Q. (2015). Fiscal decentralization and environmental pollution: Evidence from Chinese panel data. China Econ. Rev. *36*, 86–100. https://doi.org/10.1016/j.chieco.2015.08.010.
109. Li, W., Gu, Y., Liu, F., and Li, C. (2019). The effect of command-and-control regulation on environmental technological innovation in China: a spatial econometric approach. Environ. Sci. Pollut. Res. Int. *26*, 34789–34800. https://doi.org/10.1007/s11356-018-3678-3.
110. Cao, W., Zhang, Y., and Qian, P. (2019). The effect of innovation-driven strategy on green economic development in China—An empirical study of smart cities. Int. J. Environ. Res. Publ. Health *16*, 1520. https://doi.org/10.3390/ijerph16091520.
111. Yin, C., Yao, X., and Sun, B. (2022). Population density and obesity in rural China: Mediation effects of car ownership. Environ. Times *105*, 103228. https://doi.org/10.1016/j.trd.2022.103228.
112. Cai, X., Zhu, B., Zhang, H., Li, L., and Xie, M. (2020). Can direct environmental regulation promote green technology innovation in heavily polluting industries? Evidence from Chinese listed companies. Sci. Total Environ. *746*, 140810. https://doi.org/10.1016/j.scitotenv.2020.140810.
113. Zhang, T., and Wang, W. (2023). The spatial spillover effects of establishing free trade pilot zones on FDI: Empirical evidence from China. Heliyon *9*, e20587. https://doi.org/10.1016/j.heliyon.2023.e20587.
114. Bhupendra, K.V., and Sangle, S. (2015). What drives successful implementation of pollution prevention and cleaner technology strategy? The role of innovative capability. J. Environ. Manag. *155*, 184–192. https://doi.org/10.1016/j.jenvman.2015.03.032.
115. Fang, T., Fang, D., and Yu, B. (2022). Carbon emission efficiency of thermal power generation in China: Empirical evidence from the micro-perspective of power plants. Energy Pol. *165*, 112955. https://doi.org/10.1016/j.enpol.2022.112955.
116. Li, L., Raza, M.Y., and Cucculelli, M. (2024). Electricity generation and CO2 emissions in China using index decomposition and decoupling approach. Energy Strategy Rev. *51*, 101304. https://doi.org/10.1016/j.esr.2024.101304.
117. Yu, H., Wang, J., Hou, J., Yu, B., and Pan, Y. (2023). The effect of economic growth pressure on green technology innovation: Do environmental regulation, government support, and financial development matter? J. Environ. Manag. *330*, 117172. https://doi.org/10.1016/j.jenvman.2022.117172.
118. Wu, T., Wen, L., and Yi, M. (2024). Balancing growth targets and environmental regulations: An empirical analysis of dual policy impact on corporate environmental responsibility–insights from China. J. Environ. Manag. *355*, 120500. https://doi.org/10.1016/j.jenvman.2024.120500.
119. Blackman, A., and Kildegaard, A. (2010). Clean technological change in developing-country industrial clusters: Mexican leather tanning. Environ. Econ. Pol. Stud. *12*, 115–132. https://doi.org/10.1007/s10018-010-0164-7.
120. Appiah, K., Worae, T.A., Yeboah, B., and Yeboah, M. (2022). The causal nexus between trade openness and environmental pollution in selected emerging economies. Ecol. Indicat. *138*, 108872. https://doi.org/10.1016/j.ecolind.2022.108872.
121. Chen, F., Wang, M., and Pu, Z. (2022). The impact of technological innovation on air pollution: Firm-level evidence from China. Technol. Forecast. Soc. Change *177*, 121521. https://doi.org/10.1016/j.techfore.2022.121521.
122. Chen, J., Wu, L., Hao, L., Yu, X., and Streimikiene, D. (2024). Does the import of green products encourage green technology innovation? Empirical evidence from China. Technol. Forecast. Soc. Change *200*, 123137. https://doi.org/10.1016/j.techfore.2023.123137.
123. Dong, S., Ren, G., Xue, Y., and Liu, K. (2023). How does green innovation affect air pollution? An analysis of 282 Chinese cities. Atmos. Pollut. Res. *14*, 101863. https://doi.org/10.1016/j.apr.2023.101863.
124. Liu, H., Khan, I., Zakari, A., and Alharthi, M. (2022). Roles of trilemma in the world energy sector and transition towards sustainable energy: A study of economic growth and the environment. Energy Pol. *170*, 113238. https://doi.org/10.1016/j.enpol.2022.113238.
125. Din, A.U., Ming, J., Rahman, I.U., Han, H., Yoo, S., and Alhrahsheh, R.R. (2023). Green road transportation management and environmental sustainability: The impact of population density. Heliyon *9*, e19771. https://doi.org/10.1016/j.heliyon.2023.e19771.
126. Li, J., See, K.F., and Chi, J. (2019). Water resources and water pollution emissions in China's industrial sector: A green-biased technological progress analysis. J. Clean. Prod. *229*, 1412–1426. https://doi.org/10.1016/j.jclepro.2019.03.216.
127. Qamruzzaman, M. (2023). An asymmetric nexus between clean energy, good governance, education and inward FDI in China: Do environment and technology matter? Evidence for chines provincial data. Heliyon *9*, e15612. https://doi.org/10.1016/j.heliyon.2023.e15612.
128. Yu, Y.Z., Yang, X.Z., and Zhang, S.H. (2019). Research on the characteristics of time and space conversion of China's economy from high-speed growth to high-quality development. J. Quant. Tech. Econ *36*, 3–21. https://doi.org/10.1016/j.habitatint.2021.102458.
129. Zhao, X., Sun, C., Zhong, Z., Liu, S., and Yang, Z. (2023). Effect of market structure on renewable energy Development-A simulation study of a regional electricity market in China. Renew. Energy *215*, 118911. https://doi.org/10.1016/j.renene.2023.118911.
130. Farooq, U., Wen, J., Tabash, M.I., and Fadoul, M. (2024). Environmental regulations and capital investment: Does green innovation allow to grow? Int. Rev. Econ. Finance *89*, 878–893. https://doi.org/10.1016/j.iref.2023.08.010.
131. Shuai, S., and Fan, Z. (2020). Modeling the role of environmental regulations in regional green economy efficiency of China: Empirical evidence from super efficiency DEA-Tobit model. J. Environ. Manag. *261*, 110227. https://doi.org/10.1016/j.jenvman.2020.110227.
132. Li, F.J., Yang, H.W., Ayyamperumal, R., and Liu, Y. (2022). Pollution, sources, and human health risk assessment of heavy metals in urban areas around industrialization and urbanization-Northwest China. Chemosphere *308*, 136396. https://doi.org/10.1016/j.chemosphere.2022.136396.
133. Marques, A.C., and Caetano, R.V. (2022). Do greater amounts of FDI cause higher

pollution levels? Evidence from OECD countries. J. Pol. Model. *44*, 147–162. https://doi.org/10.1016/j.jpolmod.2021.10.004.

134. Li, R., Wang, Q., Han, X., and Yang, X. (2023). Trajectory and drivers of China's consumption-based and production-based renewable energy consumption. Energy Strategy Rev. *47*, 101083. https://doi.org/10.1016/j.esr.2023.101083.

135. Yao, T., Huang, Z., and Zhao, W. (2020). Are smart cities more ecologically efficient? Evidence from China. Sustain. Cities Soc. *60*, 102008. https://doi.org/10.1016/j.scs.2019.102008.

136. Wang, X., Wang, Y., and Liu, N. (2023). Does environmental regulation narrow the north-south economic gap? Empirical evidence based on panel data of 285 prefecture-level cities. J. Environ. Manag. *340*, 117849. https://doi.org/10.1016/j.jenvman.2023.117849.

137. Yang, T., and Zhou, B. (2024). Local FinTech development, industrial structure, and north-south economic disparity in China. Int. Rev. Financ. Anal. *93*, 103119. https://doi.org/10.1016/j.irfa.2024.103119.

138. Yuan, B., Ren, S., and Chen, X. (2017). Can environmental regulation promote the coordinated development of economy and environment in China's manufacturing industry? –A panel data analysis of 28 sub-sectors. J. Clean. Prod. *149*, 11–24. https://doi.org/10.1016/j.jclepro.2017.02.065.

139. Liu, Z., Fang, C., Sun, B., and Liao, X. (2023). Governance matters: Urban expansion, environmental regulation, and PM2.5 pollution. Sci. Total Environ. *876*, 162788. https://doi.org/10.1016/j.scitotenv.2023.162788.

140. Cui, H.y., and Cao, Y.q. (2022). Do smart cities have lower particulate matter 2.5 (PM2.5)? Evidence from China. Sustain. Cities Soc. *86*, 104082. https://doi.org/10.1016/j.scs.2022.104082.

141. Wang, N., Wei, C., Zhao, X., Wang, S., Ren, Z., and Ni, R. (2023). Does green technology innovation reduce anthropogenic PM2.5 emissions? Evidence from China's cities. Atmos. Pollut. Res. *14*, 101699. https://doi.org/10.1016/j.apr.2023.101699.

142. Zhang, Z., Zhou, Z., Zeng, Z., and Zou, Y. (2023). How does heterogeneous green technology innovation affect air quality and economic development in Chinese cities? Spatial and nonlinear perspective analysis. J. Innov. Knowl. *8*, 100419. https://doi.org/10.1016/j.jik.2023.100419.

143. Yilanci, V., Bozoklu, S., and Gorus, M.S. (2020). Are BRICS countries pollution havens? Evidence from a bootstrap ARDL bounds testing approach with a Fourier function. Sustain. Cities Soc. *55*, 102035. https://doi.org/10.1016/j.scs.2020.102035.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
environmental pollution intensity	*China Statistical Yearbook; China Environmental Statistics Yearbook*	https://www.stats.gov.cn/; https://cnki.nbsti.net/
high-quality innovation	*China Statistical Yearbook; China's State Intellectual Property Office*	https://www.stats.gov.cn/;http://www.cnpat.com.cn/
economic development	*China Statistical Yearbook*	https://www.stats.gov.cn/
population density	*China Statistical Yearbook*	https://www.stats.gov.cn/
energy consumption intensity	China Statistical Yearbook; China Energy Statistical Yearbook; *China Environmental Statistics Yearbook*	https://www.stats.gov.cn/; https://cnki.nbsti.net/
foreign direct investment	China Statistical Yearbook	https://www.stats.gov.cn/
rationalization of industrial structure level	China City Statistical Yearbook	https://cnki.nbsti.net/
energy transition	Energy Statistic Yearbook; China Electric Power Yearbook	https://cnki.nbsti.net/
environmental regulation	China City Statistical Yearbook	https://cnki.nbsti.net/
Software and algorithms		
Stata	StataCorp LLC	https://www.stata.com/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Yun Tang (tangyun@ucas.ac.cn).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- This paper analyzes existing, publicly available data. These accession numbers for the datasets are listed in the key resources table.
- Code for the analysis was written in STATA and is available from the lead contact upon reasonable request.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Two-stage least squares (2SLS) regression method

This article empirically examines the impact of HI on EP of China's 31 provinces by Two-Stage Least Squares (2SLS) regression method, and provincial panel data. The benchmark regression is denoted as Equation:

$$EP_{it} = \alpha_0 + \alpha_1 HI_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 5)}$$

where EP is environmental pollution. HI is high-quality innovation. i and t show province and year, separately. ε_{it}, μ_i and λ_t represent error term, province fixed, and year fixed effect, respectively. α_i (i=1, …, n) are the corresponding coefficients. X_{it} is matrix of control variables, including foreign direct investment (FDI), population density (PD), economic development (ED), rational industrial structure (RIS), and energy consumption intensity (EC).

Then, this paper selects energy transition (ET_{it}) as an important mediating variable, which affect the correlation between HI and EP. X_{it} represents control variables that are consistent with Equation 5. Therefore, the mediating effect models are constructed as follows:

$$ET_{it} = \beta_0 + \beta_1 HI_{it} + \beta_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 6)}$$

$$EP_{it} = \beta_3 + \beta_4 HI_{it} + \beta_5 ET_{it} + \beta_6 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 7)}$$

where β_i presents the corresponding coefficients. Especially, when coefficients of β_1, β_4, and β_5 are significant, which demonstrates ET_{it} has a significant mediating function in the connection between HI and EP.

Further, this paper chooses environmental regulation (ER_{it}) as moderating variable, and discusses its role in the association between HI and EP. Therefore, the moderating effect model is built as follows:

$$EP_{it} = \gamma_0 + \gamma_1 HI_{it} + \gamma_2 X_{it} + \gamma_3 ER_{it} + \gamma_4 ER_{it} * HI_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 8)}$$

where γ_i shows the corresponding coefficients. Especially, when coefficients of γ_3 and γ_4 are significant, indicating ER_{it} provides a clear moderating effect on the interaction between HI and EP.

The two-stage least squares (2SLS) method is a regression modeling approach that can handle violations of the ordinary least squares (OLS) assumption, thereby addressing issues such as heteroscedasticity, multicollinearity, autocorrelation, and endogeneity.[77–79] As a result, the 2SLS-estimated equations are more accurate in capturing the causal and feedback effects among the system's primary factors as well as the interactions between the equations.[80] The superior performance of this method has led to its widespread application in various fields, including financial markets,[81] the environment,[82] and corporate finance.[83]

QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses were performed in Stata.