Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-03924-3 OPEN

Check for updates

Identifying the antecedents for the green transformation of resource-exhausted cities in China

Yanchao Feng [1], Yue Gao[1] & Yuxi Pan[1]✉

To address the issue of green transformation in resource-exhausted cities, this study employs the Policy Modeling Consistency (PMC) index model to carry out a comprehensive analysis of the effectiveness of support policies execution at both central and local levels, covering 16 policies at the different administrative levels. Meanwhile, utilizing the fuzzy-set Qualitative Comparative Analysis (fsQCA) method, the study investigates the interaction mechanisms and effects of various internal and external factors in the context of policy coordination, from the perspective of green transformation condition configurations. The findings reveal that the overall effect of supporting policies for resource-exhausted cities in China is generally commendable. Moreover, there is a notable characteristic that "the lower the administrative level, the higher the quality of the support policies". Notably, organizational, technological, environmental, and policy conditions alone cannot solely facilitate the green transition of resource-exhausted cities. Instead, it is the harmonious configuration of these antecedents that drives successful green transformation. Additionally, the configuration of antecedent conditions for green transformation exhibits the heterogeneity of different types. Specifically, the eastern region primarily relies on technological innovation and production process improvement, while the central region focuses on both production process improvement and support policy combinations. By contrast, the western region primarily emphasizes support policy combinations and the fostering of environmental conditions. Furthermore, the green transformation of resource-exhausted cities with coal and oil types mainly depends on the combination of policy support and technological innovation. Metal, forestry, and other types of resource-exhausted cities rely on the upgrading and advancement of industrial structures. In the grouped analysis of administrative level, innovation capability, and distance to the provincial capital city, cities with higher administrative levels, higher innovation capabilities, and closer proximity to the provincial capital city are more likely to achieve green transformation. Thereby, this study emphasizes the critical role of support policies and the identification of effective pathways in promoting the green transformation of resource-exhausted cities.

[1] Business School, Zhengzhou University, High-tech District, Zhengzhou 450001, China. ✉email: yuxipan@gs.zzu.edu.cn

Introduction

Over the past 30 years, China has gradually become the world's second-largest economy, marked by a remarkable and unique pace of expansion (Wu, 2000). The efficacy of China's economy is closely tied to its abundant mineral resources and the advancement of resource-based cities. As is well known, China is renowned as a significant mineral resource powerhouse, rich in reserves and production of diverse minerals encompassing coal, petroleum, natural gas, metals, and non-metals. Specifically, some of these mineral resources rank among the highest globally in terms of reserves and production levels (He et al. 2023). The exploitation of mineral resources and the growth of resource-based cities have provided a crucial material foundation and energy security for China's rapid economic expansion, supporting processes such as industrialization, urbanization, and technological advancement (Shi et al. 2024). This has contributed to the increase in national income and the enhancement of people's living standards (Li et al. 2023). However, from a dialectical perspective, the adverse effects of this extensive economic development model cannot be overlooked (Yahman and Setyagama, 2023). Resource-based cities face various challenges such as resource depletion and decline, economic homogenization, and low-end development, as well as environmental degradation and deterioration (Dou et al. 2023). These phenomena suggest that the traditional "winning by quantity" standard is no longer sufficient to satisfy the requirements of economic growth in the new era. Instead, there is a gradual shift towards the new requirement of "winning by quality" (Dreyer, 2018). This shift necessitates a reevaluation of development ideologies and models for China's resource-based cities.

Against this backdrop, the call for "high-quality development" introduced in the 19th National Congress report in 2017 in China has brought increasing attention to the development mode of green transformation (Yang et al. 2023). Discovering a greener, more sustainable, and higher-quality growth trajectory has emerged as a major challenge for attaining high-quality economic development in China and globally (Wang et al. 2021). Specifically, to address the challenges of a single industrial structure and unsustainable economic development in resource-exhausted cities, the Chinese government has successively implemented numerous central policies designed to achieve green transformation and upgrading (Wang et al. 2023). Notably, there are several milestone policies in this process. For instance, the "Several Opinions on Promoting the Sustainable Development of Resource-Based Cities" issued by the State Council in 2007 called for increased support for sustainable development, particularly in cities facing mineral resource depletion. The "National Plan for the Sustainable Development of Resource-Based Cities (2013–2020)" was released in 2013 to further promote sustainable development. The "14th Five-Year Plan for Promoting the High-Quality Development of Resource-Based Regions," released in 2021, emphasized the integral role of promoting high-quality development in these regions for achieving regional coordinated development and addressing transformation and development challenges. The shift in policy focus reflects the evolving landscape of green transformation and underscores the government's commitment to sustainable development. Therefore, it is evident that these supporting policies have provided a crucial institutional foundation for the green transition of resource-exhaused cities in China, guiding their development goals and practical approaches (Li et al. 2013).

Promoting green transition in resource-exhaused cities is a crucial and challenging task that urgently requires a deep understanding of its driving factors and strategic pathways to efficiently achieve sustainable and high-quality development in these cities. To the best of our knowledge, the existing research primarily focuses on two main directions, namely the measurement of urban green transformation and its driving factors. From one aspect, in terms of measuring green transition in resource-exhaused cities, current studies tend to construct comprehensive indicators to assess the degree of urban green development from a diversified perspective. For instance, Chen et al. (2018) employed an improved TOPSIS method and sequential weighting method to systematically consider the sustainable development characteristics of target cities from the aspects of economic adjustment, social progress, and environmental improvement. Additionally, other factors such as strategic innovation, resource endowment, and intelligence are also key internal indicators considered by scholars (Yu et al. 2005; Zhang et al. 2018). From another aspect, existing research focuses on exploring the driving factors of green transition in resource-exhaused areas from two perspectives, including external environment and internal factors. In detail, external environment factors primarily encompass national macro policies, such as those specifically tailored to support resource-exhausted cities (Wu et al. 2023) and sustainable development planning policies (Wang et al. 2022). These policies have been empirically proven to facilitate green transformation. Additionally, governments can also enforce stringent environmental regulations to encourage enterprises to upgrade and transform, thereby reducing the dependency of resource-exhausted cities on traditional fossil fuels (Yang and Wang, 2023; Kalair et al. 2021). From an internal perspective, the scholars have identified that green technology innovation (Sun and Zhang, 2022), optimization of energy structures through the adoption of new energy sources (Guo et al. 2018), and human capital structure optimization can be regarded as effective means to achieve green transition in resource-exhaused cities (Shen et al. 2023). Thereby, existing research has laid a solid foundation for measuring the green transition of resource-exhaused cities, emphasizing that urban green sustainable development planning tends to follow a unified framework balancing social, economic, and environmental aspects from the outset (Liu et al. 2021). It is also evident that most existing quantitative studies assume the independence of influencing factors, exploring the impact of individual antecedent variables on green transition. However, in practice, the combined effect of these variables is more significant. Namely, in the context of policy coordination, it is imperative to investigate the interaction mechanisms and overall impact of various internal and external factors. This constitutes one of the initial research motivations of this study.

To address this, this study centers on examining the effects of policy execution and decentralization on support measures for resource-exhaused cities, meanwhile it aims to explore effective mixed methods for achieving green transformation within a structured policy framework. To accomplish this point, we employ two primary analytical methods. Firstly, the PMC model is employed to quantitatively evaluate the supporting policies for the chosen resource-exhausted cities. This approach offers a visual representation of each policy's strengths and weaknesses, enabling a comparison of the highest and lowest-scoring policies with the average score to assess their feasibility. Secondly, the fsQCA method is introduced to refine the effective paths for resource-exhaused cities to achieve the green transition. This method illustrates the implementation of each path combination through real-world city examples, while also elucidating the reasons for the emergence of such path combinations in the Chinese context. In comparison to existing literature, the marginal contributions of this paper are reflected in three folds. Firstly, the innovative application of the PMC index model to assess the effectiveness of supporting policies in resource-exhausted cities provides a clearer and more intuitive understanding of policy performance, thereby facilitating further policy improvement and introduction. Secondly, it also comprehensively analyzes the blend of paths for green transformation in resource-exhaused cities relying on the fuzzy set qualitative comparative analysis, considering four dimensions: organizational conditions, technological advancements, economic factors, and environmental sustainability. Finally, this paper provides an extensive and systematic insight into tackling the challenges faced by resource-exhaused cities in emerging economies and countries worldwide, with a focus on green transformation and sustainable development.

The rest of this study is structured as follows: Section two covers the theoretical analysis of frameworks for green transformation in resource-exhausted cities. Section three details the research design. Section four presents a quantitative assessment of supporting policies. Section five identifies causal factors for green transformation. The final section offers conclusions, policy implications, and research prospects.

Theoretical analysis

The current economic and social development mode in China is centered around the concept of "high-quality development," which encompasses five key dimensions, innovation, coordination, green development, openness, and shared prosperity (Luttropp and Lagerstedt, 2006; Bei, 2018). These principles guide various strategies and policies, including the green transition of resource-exhaused cities. This transformation is not limited to environmental considerations alone (Song et al. 2017; Uralovich et al. 2023), rather, it demands a holistic approach that involves the restructuring of economic structures, enhancing social welfare, fostering regional cooperation, and improving competitiveness (Hou et al. 2018; Dou and Gao, 2023). The ultimate goal is to establish a sustainable, inclusive, environmentally friendly, and highly competitive urban development model. Based on this, this paper aligns with the macro guidance of national policies promoting high-quality development in analyzing the conditions for green transformation in these cities. It attempts to conduct an in-depth analysis from four dimensions, including organizational structure, technological upgrading, environmental optimization, and supporting policies. Furthermore, the paper delves into the intricate relationships and alignment conditions among these dimensions, aiming to offer insights and recommendations for effective implementation strategies. By examining the green transition of resource-exhaused cities through the lens of high-quality development, aiming to contribute to the development of sustainable urban models that balance economic growth, social welfare, and ecological preservation (Ruan et al. 2020). It is hoped that the insights gained from this analysis will inform policymakers and stakeholders in their efforts to foster green and inclusive urban development in China and beyond.

Organizational structure, as the foundational framework of any economic system, serves as a pivotal element for maintaining its stability and ensuring efficient operations (Pollard et al. 2023). It is imperative to highlight that a scientifically rational organizational framework not only significantly boosts the overall efficiency of the economic system but also ensures coordinated operations among its internal branches, facilitating the seamless progression of various work processes (Karpenko et al. 2023). Especially in cities confronted with resource depletion challenges, the adjustment and restructuring of organizational structures carry strategic significance, aiming to steer cities toward successful transformation into green and sustainable development models. In this green transformation process, the "green" concept holds a central position, implying that environmental management departments and economic policy-making departments must engage in deep cooperation. For instance, it is crucial to jointly promote green reforms from the outset of the industrial chain, encompassing raw material acquisition, processing, and other aspects, along with the complete green upgrading of the industrial structure. Additionally, embedding green development elements throughout the entire process of economic development is imperative (Song et al. 2023; Haibo et al. 2023).

Technological upgrading is the driving force of economic development, which could pose a significant multiplier effect on the economy (Khan and Haneklaus, 2023). The accomplishment of green transition in resource-exhaused cities necessarily hinges on the robust endorsement and widespread utilization of green technology. Green technology encompasses various innovative approaches, such as clean energy technology, energy efficiency and emission reduction technology, and efficient utilization and alternative resource development technologies (Shan et al. 2021). These innovations extend from energy utilization and production process optimization to waste management and ecosystem restoration. Technological capability innovation not only enables urban economic systems to break free from excessive reliance on traditional resources and facilitates low-carbon and clean upgrades in industrial structure, but also reduces pollution emissions at the source and enhances resource utilization efficiency by establishing circular economy models (Ebhota and Jen, 2020; Liang and Tan, 2024). The green transformation of resource-exhausted cities necessitates technical support steered by green technology, which necessitates the comprehensive mobilization and integration of efforts from the government, enterprises, and other stakeholders to expedite the conversion of technological achievements into tangible productive forces (Jahanger et al. 2022).

External environment optimization is equally crucial for the green transition of resource-exhaused cities, and this supporting effect originates from multiple aspects, including the social context, ecological environment, and business environment (Awan, 2013). Firstly, effective social governance mechanisms, enhanced public engagement awareness, and the cultivation of a culture of sustainable development constitute the societal foundation for this transformation, ensuring a robust and orderly process (Dewulf et al. 2015). Secondly, the quality of the ecological environment acts as a vital natural support, with measures such as soil and water conservation, pollution control, biodiversity conservation, and green development space planning aimed at restoring and safeguarding the environment (Pearce and Turner, 1989). These measures not only alleviate the damage caused by resource extraction but also transform natural resource advantages into new development opportunities, fostering a harmonious and symbiotic urban development model with nature (Yang et al. 2019). Lastly, the optimization of the business environment is pivotal in attracting green investments, fostering emerging industries, and guiding the green transformation of traditional industries (Ahmadova et al. 2022). Governments and enterprises must prioritize the creation of a business environment that encourages healthy market competition, one that is open, transparent, fair, and filled with innovative vitality. This environment can motivate enterprises to adopt environmentally friendly technologies and management practices, accelerate the formation of a green industrial chain, and aid resource-exhausted cities in achieving green upgrades of their economic structures and adjustments in their industrial structures (Zhu et al. 2023).

Complementary government policies provide strong support for the green transition of resource-exhausted cities (Chen et al. 2024). The implementation of pertinent government policies, encompassing financial assistance, talent allocation, and technological advancements, can effectively facilitate the attainment of green transformation (Zhai and An, 2020). Specifically, financial

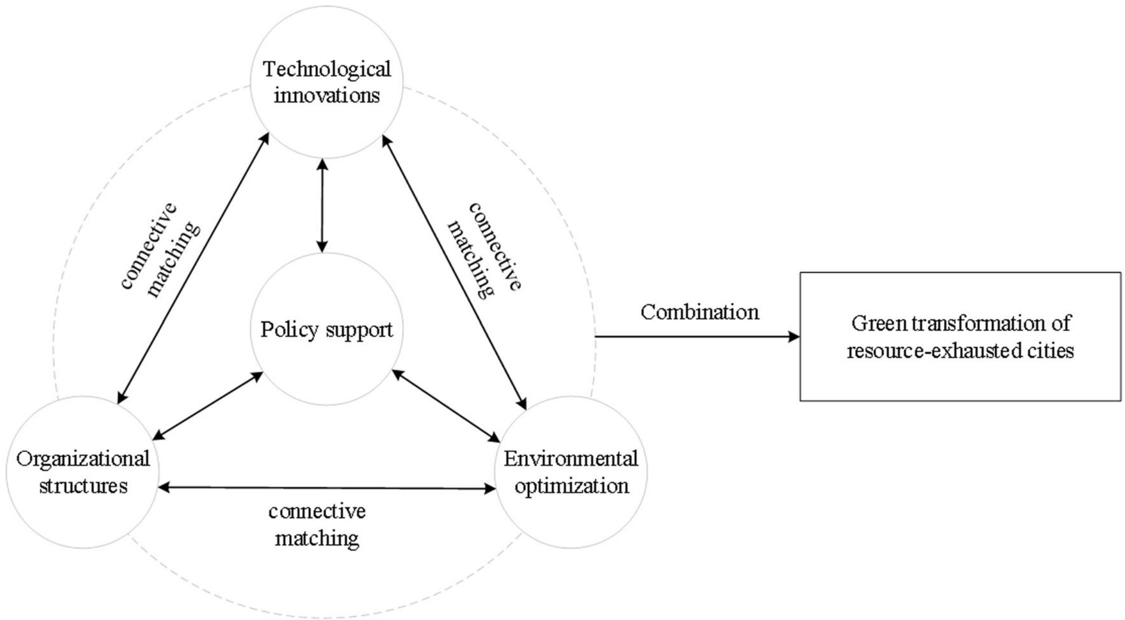

Fig. 1 Mechanism for green transformation of resource-exhausted cities.

backing fosters the R&D and advancement of green technology (Lv et al. 2021), while also establishing specialized zones dedicated to green economic growth (Wang and Wang, 2022). These zones serve as viable platforms for economic advancement, attracting diverse capital and enterprises, and ultimately leading to a diversified economic landscape (Luo et al. 2022). Additionally, the allocation of skilled technical personnel and the availability of cutting-edge technology not only propel economic diversification (Khasawneh, 2024) but also act as a catalyst for the green transition of resource-exhaused cities. The introduction of advanced technology effectively drives the transformation of industrial structures (Maddikunta et al. 2022), while skilled technical personnel ensure the continuation of technological advancement, ensuring a seamless green transformation process.

China's economic and social development largely relies on top-down information dissemination and strategic guidance, highlighting the significant role of government policies in steering economic and social progress. Specifically, the green transformation of resource-exhausted cities necessitates macro-level steering by the state, with the formulation of pertinent policies tailored to the cities' actual development trajectory. This involves fine-tuning organizational frameworks, facilitating technological innovation-related services, and concurrently urging the environmental sector to undertake tasks pertaining to environmental preservation and enhancement. Essentially, in many cases, government policies act both as a protective umbrella and a compass. They encompass elements such as organizational restructuring, technological innovation, and environmental optimization, and also determine the direction for the development and improvement of these sub-elements. In turn, the actual progress achieved in these areas provides valuable feedback for the government to adopt more targeted and responsive measures. Thereby, the green transition of resource-exhaused cities is a concerted effort that necessitates the synergistic action of multiple forces, and these forces constitute a vital impetus propelling the green transition of resource-exhausted cities.

In other words, the effective combination of key forces-enterprise implementation in organizational and technological aspects, public cooperation in the external environment, and government-led supporting policies-forms the crucial linkage mechanism for facilitating the green transformation of resource-exhausted cities (Peng et al. 2023). Figure 1 vividly portrays the mechanism for realizing green transition in target cities.

Research design

To assess the supporting policies of resource-exhausted cities in a more tangible manner, we employ the PMC index for evaluation purposes. This index serves as a valuable tool for evaluating the effectiveness of policy implementation, utilizing quantitative and objective metrics to assess the degree of policy goal achievement, standardization, and efficiency throughout the execution process, as cited by Zhao et al. (2023) and Kuang et al. (2020). The PMC index model is constructed upon the establishment of a policy evaluation index system, utilizing secondary variable assignment criteria for scoring. When the text concerns relevant content, it is deemed compliant and assigned a value of 1, whereas non-compliance is assigned a value of 0. This ensures that the variables adhere to the [0,1] distribution, as represented in the following model. By calculating the value of each level 1 variable for each policy, we determine the PMC index for each support policy, which indicates the level of policy implementation effectiveness.

$$X \sim N[0,1] \tag{1}$$

$$X = \{XR: [0 \sim 1]\} \tag{2}$$

$$X_i = \sum_{j=1}^{n} \frac{X_{ij}}{n(X_{ij})} \tag{3}$$

$$\mathrm{PMC} = \sum_{j=1}^{m} X_i = \sum_{j=1}^{m} \left(\sum_{j=1}^{m} \frac{X_{ij}}{n(X_{ij})} \right) \tag{4}$$

where i denotes the primary variables, j denotes the secondary variable, X_{ij} denotes the value of a particular secondary variable, and n denotes the number of secondary variables under a particular primary variable, m denotes the number of primary variables.

Furthermore, the PMC surface diagram serves as a visual representation of the PMC index results, facilitating the visualization of each policy's evaluation outcomes in a three-dimensional format. Specifically, the PMC surface's concave and convex shapes indicate the index level, while distinct color

Table 1 List of resource-exhausted cities by time and batch.

Time and batch	List of selected cities
Identification of 12 cities as the first batch of resource-exhausted cities in the country in 2008	Fuxin City, Yichun City, Liaoyuan City, Baishan City, Panjin City, Shizuishan City, Baiyin City, Wulumu City (county-level city), Jiaozuo City, Pingxiang City, Daye City (county-level city), Daxinganling District
Identification of 32 cities as the second batch of resource-exhausted cities in 2009	Zaozhuang City, Huangshi City, Huaibei City, Tongling City, Qitaihe City, Wansheng District (prefecture-level city), Fushun City, Tongchuan City, Jingdezhen City, Wanshan District of Tongren, Yumen City, Qianjiang City, Lingbao City, Heshan City, Leiyang City, Lengshuijiang City, Beipiao City, Shulan City, Huaying City, Jiutai City, Zixing City, Zhongxiang City, Xiaoyi City, Wudalianchi City, Aershan City, Dunhua City, Yangjiazhangzi Mining District, Yingshouyingzi Mining District, Nanpiao District, Dongchuan District, Gongchangling District, Xiahuayuan District
Identification of 25 cities as the third batch of resource-exhausted cities in 2011	Hegang City, Shuangyashan City, Xinyu City, Puyang City, Shaoguan City, Luzhou City, Wuhai City, Jingfu Mining District, Huozhou City, Shiguai District, Erdaojiang District, Wangqing County, Jiawang District, Dayu County, Xintai City, Zichuan District, Songzi City, Lianyuan City, Changning City, Pinggui Management District, Changjiang County, Nanchuan District, Yimen County, Tongguan County, Honggu District

blocks denote numerical disparities. To generate the PMC surface diagram, the initial step involves constructing the PMC matrix, with the matrix's variables corresponding to various levels of variables. The study set 9 first-level variables, so the PMC surface matrix is shown as formula (5).

$$\text{PMC surface matrix}\begin{bmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{bmatrix} \tag{5}$$

Besides, this study also adopts the fuzzy set qualitative comparative analysis method (Mendel and Korjani, 2013; Huarng, 2016) to assess the combined factors influencing the green transformation of resource-exhausted cities. This analysis encompasses four key dimensions, organizational frameworks, technological advancements, environmental factors, and policy environments.

The so-called resource-exhausted city is that cities have reached a late, mature, or conclusive phase in the exploitation of their mineral resources, having extracted over 70% of recoverable reserves. These are confronted with numerous challenges, including dwindling resources, degrading ecosystems, and waning economic fortunes, necessitating transformation and revitalization efforts to secure their long-term sustainability. Over the course of three separate batches in 2008, 2009, and 2012, a total of 69 cities, counties, and districts were officially recognized as resource-exhausted cities (The list of selected cities is shown in Table 1).

During the period from 2003 to 2018, China achieved relatively rapid development, with a swift increase in economic size and a substantial expansion of industrial scale. Utilizing data from this phase can provide more accurate identification of the causes driving green transformation in resource-exhausted cities. Secondly, the force majeure factor of the COVID-19 pandemic that occurred at the end of 2019 may incur non-anthropogenic biases in the identification of causes, ultimately affecting the credibility of the research. Finally, after 2018, China's development embarked on a substantial kinetic energy transformation, with the resource support undergoing significant changes. The energy structure shifted from one primarily reliant on coal and oil to one dominated by new energy sources. This transformation might amplify the effect of new energy on achieving green transformation while underestimating the influence of other factors, potentially leading to biases in identification. Based on the above three reasons, after careful consideration, we have decided to utilize data from 2003 to 2018 to conduct a study on the antecedent causes of green transformation in 69 resource-exhausted cities, while updating the policies to 2022. To ensure consistency in administrative levels, the data for cities and counties were harmonized to a municipal administrative level, resulting in a total of 56 cities for analysis.

The primary outcome variable is green transformation, measured using a composite indicator. It represents a shift towards sustainable development, driven by ecological civilization, a circular economy, and green management. This shift involves transitioning from traditional development models to scientific ones, emphasizing harmony between humans and nature, and coordinating economic, social, and ecological development. In other words, this transformation makes the connotation of green transformation more stereoscopic and intuitive, integrating economic, social, and ecological aspects. Therefore, the measurement focuses on economic transition, social transition, and environmental transition. The detailed proxies are shown as follows: firstly, economic transformation is mainly reflected in the increase of GDP and government fiscal expenditure, which is measured by the proportion of the tertiary industry's output in the total output, and a higher proportion indicates a more successful economic transformation. Secondly, the evaluation of society's quality is mainly conducted in terms of average education level and residents' qualities. The development of social transformation towards a higher level implies a higher average education level and improved qualities of residents. Thirdly, the environmental transformation is the key to embodying "greenness". Against the backdrop of the "dual carbon goals", carbon emissions are the best indicator to measure the quality of the environment, and lower carbon emissions indicate a better environment. Finally, the green transformation composite index is then computed using the entropy weight method.

The realization of green transformation does not happen overnight. It requires the concerted efforts of multiple parties, as well as the participation of both the government and society. Reasonable organization and management serve as the hub for coordinating these efforts, enhancing the efficiency of the transformation. Technological innovation is a crucial force driving the achievement of green innovation, and the use of green technologies can accelerate the process of transformation. The market competition environment serves as an "umbrella" safeguarding the normal operation of the economic system, providing a favorable competitive platform for all parties involved in the transformation. Government policies, as the "lighthouse", guide the direction of the green transformation, providing strategic guidance at the macro level to ensure the smooth progress of

Table 2 Variable definitions.

Variables

Outcome variable	Secondary	Expression	Formula
Green transformation (GTI)	Economic transformation	Per capita GDP	The ratio of GDP to population
		Share of tertiary production value	The ratio of tertiary to total output
		fiscal expenditure	The ratio of fiscal expenditure to GDP
	Social transformation	Percentage of college students	The ratio of college students to the total population
		population density	The ratio of population to the area
		Urban green coverage	The ratio of green area to the total area
	Environmental transformation	Industrial electricity consumption	The ratio of industrial to total electricity consumption
		CO_2 emissions	Industrial CO_2 emissions
		Solid waste utilization rate	The ratio of solid waste utilization to total

Antecedent variables	Secondary	Expression	Formula
Organizational conditions	Management model change (MMC)	Expressed as the capital-labor ratio	The ratio of capital stock to the labor force
	Production process improvement (PPI)	Expressed as an index of industrial structure	primary industry x 1 + secondary industry x 2 + tertiary industry x 3
Technological conditions	Technological innovation (TI)	The ratio of technology R&D expenditures to GDP expressed	The ratio of R&D expenditures to GDP
	Infrastructure development (ID)	Area of paved roads per capita	The ratio of total road area to population
Environmental conditions	Market competition pressure (MCP)	Expressed as foreign direct investment	The ratio of total FDI to GDP
	Industrial development level (IDL)	Expressed as secondary sector ratio	The ratio of secondary to total output
Policy conditions	Support policy combinations (SPC)	Expressed as a dummy variable	Presence is 1, absence is 0

transformation activities. Accordingly, the antecedent variables are categorized into four areas, organizational frameworks, technological advancements, environmental conditions, and policy environments. A comprehensive listing of all variables is provided in Table 2. The data used in this analysis is sourced exclusively from the China Urban Statistical Yearbook.

Policy quantitative evaluation

Selection and classification of policy texts. In the process of selecting supporting policy documents for resource-exhausted cities, this study encompasses national, provincial, and municipal policy documents to reveal potential differences in policy-making across various geographical regions (Table 3). Specifically, it includes three national-level policies, seven provincial-level policies, and six municipal-level policies, which cover the eastern, central, western, southern, and northern regions, with a focus on the "severity of resource depletion in the region". The chosen policy documents serve as representative analysis samples, ensuring comparability, scientific validity, and rationality among the evaluated policies. Notably, all selected support policies were issued following the designation of the initial batch of resource-exhausted cities in 2007, thereby guaranteeing the reliability and credibility of the documentation. Furthermore, the structure of these policies exhibits a remarkable similarity, facilitating their comparison. Finally, the majority of the selected policies bear titles that incorporate keywords such as "resource exhaustion," "sustainable development," and "urban transformation," which are intimately connected to the advancement of resource-exhausted cities. This alignment between policy content and theme ensures a high degree of coherence and scientific rigor in the evaluation outcomes.

The construction of the PMC index model necessitates the consideration of both the focal points outlined in the supporting policy documents for resource-exhausted cities and the diverse influencing factors associated with each policy. Adhering to the established requirements and guidelines for the PMC index model's development, this study meticulously evaluated the present state of resource-exhausted cities' progress and drew insights from the preceding analysis of policy texts. Drawing upon the existing research conducted by scholars in related fields regarding PMC parameter settings, this study excluded any irrelevant or redundant vocabulary and evaluation criteria, and the final nine primary variables and forty secondary variables are identified (Table 4). These primary variables encompass policy nature (X1), policy timeliness (X2), policy level (X3), policy evaluation (X4), policy area (X5), policy guarantee (X6), policy priority (X7), policy object (X8), and policy perspective (X9).

PMC index calculation and analysis. This study adopts the PMC index to carry out a thorough consistency assessment of the support policies for resource-exhausted cities. Each policy was assigned a total score of 9 points. Drawing from the prevailing consensus among academics, the evaluation criteria for these policies were categorized into four distinct grades. Policies scoring between 8 and 9 were deemed to be "perfect," while those scoring between 7 and 8 were classified as "excellent". Policies scoring between 5 and 7 were rated as "good," while those scoring between 0 and 5 were considered to be "bad" (Zhao et al. 2023). By leveraging these standards, the PMC index for each policy was meticulously computed through the employment of Boolean operations and the corresponding formula.

Based on the results in Table 5, it is evident that the implementation of the supporting policies in resource-exhausted cities has been relatively satisfactory. The average PMC index stands at 7.160, indicating that the supporting policies have achieved an excellent grade as a whole. Specifically, among the selected policies, two of national-level policies, three of provincial-level plans and all six municipal policies have been rated as excellent grades. This analysis reveals a correlation

Table 3 Sample evaluation of supporting policies for resource-exhausted cities.

Number	Policy documents	Releasing time	Releasing organization
P1	Several Opinions of the State Council on Promoting the Sustainable Development of Resource-Based Cities ([2007] No. 38)	2007	State Council (PRC)
P2	Circular of the State Council on the issuance of the National Sustainable Development Plan for Resource-Based Cities (2013–2020) ([2013] No. 45)	2013	State Council (PRC)
P3	Opinions of the State Council on Supporting Shanxi Province to Further Deepen Reform and Promote the Transformation and Development of Resource-Based Economy ([2017] No. 42)	2017	State Council (PRC)
P4	Opinions of the General Office of the People's Government of Anhui Province on Promoting the Transformation and Sustainable Development of Resource-Based Cities ([2011]No. 42)	2011	Anhui Province
P5	Opinions of the People's Government of Guizhou Province on Supporting the Transformation and Development of Wanshan Resource-Exhausted City ([2013] No. 10)	2013	Guizhou Province
P6	Hunan Provincial People's Government on Implementation Opinions on Promoting the Sustainable Development of Resource-Based Cities ([2012] No. 20)	2012	Hunan Province
P7	Circular of Jiangxi Province on the Issuance of Opinions on Supporting the Transformation and Sustainable Development of Cities Exhausted of Resources ([2011] No. 68)	2011	Jiangxi Province
P8	Opinions of the General Office of the People's Government of Shandong Province on Supporting the Transformation and Development of Resource-Exhausted Cities ([2014] No. 99)	2014	Shandong Province
P9	Implementation Program of the 14th Five-Year Plan for Promoting High-Quality Development of Resource-Based Regions in Shanxi Province ([2022] No. 29)	2022	Shanxi Province
P10	Opinions of the General Office of the People's Government of Shaanxi Province on Strengthening Geological Search for Minerals and Promoting Sustainable Economic Development ([2013] No. 84)	2013	Shaanxi Province
P11	Program for the Transformation of Resource-Exhausted Cities in Baiyin City ([2009] No. 68)	2009	Gansu Province
P12	Opinions of the People's Government of Jiaozuo City on Accelerating the Transformation of Resource-Exhausted Cities ([2009] No. 180)	2009	Jiaozuo City
P13	Transformation and Development Plan for Resource-Exhausted Cities in Jingdezhen City (2013–2020)	2013	Jingdezhen City
P14	Transformation and Development Plan for Resource-Exhausted Cities in Pingxiang City (2013–2020)	2013	Pingxiang City
P15	Shaoguan City Resource Exhausted Cities Transformation and Development Action Plan 2016	2016	Shaoguan City
P16	Transformation and Development Plan for Resource-Exhausted Cities in Xinyu City (2013–2020)	2013	Xinyu City

between the quality of supporting policies for resource-exhausted cities and administrative levels, with a trend toward more detailed policies at lower administrative levels. This differentiation is attributed to the varying positioning and implementation intensity of policies at different levels. In other words, the national-level policies primarily focus on strategic guidance and directional setting, with relatively macroscopic content. Provincial governments formulate supporting policies that align with national strategies and local conditions, tailored to meet specific local needs. Municipal governments, while adhering to higher-level policy guidelines, place greater emphasis on the operational aspects and implementation details of policies. They are required to clearly define support measures to ensure the orderly and effective promotion of the transformation of resource-exhausted cities.

After analyzing the indicator scores and averages of various policies, it is evident that there are both differences and overlaps in the focus areas and formulation processes of the relevant policies. Firstly, Table 5 reveals that the scores and mean values for policy timeliness (X2) and policy level (X3) are identical, both standing at 0.333. This consistency in scores for policy level (X3) is due to the fact that a policy document's release level is typically designated as either national, provincial, or municipal, excluding the possibility of a document being simultaneously designated at all three levels. Similarly, the consistency for policy timeliness (X2) arises because the majority of policies have a medium to long duration, typically ranging from 3 to 5 years. It is not realistic for a policy to have both a long and a short duration. Secondly, the majority of policies in the categories of policy nature (X1), policy guarantee (X6), and policy priority (X7) scored higher than the mean. This indicates that the formulation of most supporting policies takes into account the nature, guarantee, and priority of the policy. It demonstrates a clear understanding of the purpose of the policies, the guarantees they provide, the main focus of the policy priority, and the ultimate effect that needs to be achieved through its implementation. Lastly, the scores and mean values for policy evaluation (X4), policy area (X5), policy object (X8), and policy perspective (X9) all stand at 1.000. This indicates that policy formulation involves a comprehensive range of contents and objects, encompassing both macro and micro levels, and demonstrating a high degree of integration. These scores highlight the importance of considering various perspectives and evaluation methods to ensure the policies are well-rounded and comprehensive. In conclusion, the analysis of the scores and mean values of the indicators across the policies reveals a diversified yet integrated approach to policy formulation. The policies differ in their focus areas, emphasizing different aspects, while also overlapping in terms of their objectives and guarantees. This approach ensures that the policies are tailored to their respective contexts, addressing specific issues while maintaining a holistic perspective.

Moreover, this subsection presents the PMC surface diagram, which is a staggered 3D representation constructed along the three-dimensional axes. It offers a visual representation of the PMC index's overall situation, providing a concise comprehension of the policy's performance across various levels. To illustrate the varying display effects of the surface diagrams, we have selected and presented the PMC surface diagrams for the three policies with the highest PMC values, namely P14 and P16, as well as the policy with the lowest value, P8 (presented by Figs. 2–4).

To accurately determine the most effective avenue for refining supportive policies, it is imperative to meticulously scrutinize the discrepancies that exist between each individual policy and the idealized "perfect" policy. Consequently, this investigation employs

Table 4 Variables and evaluation criteria for quantitative policy evaluation.

Primary variables	Secondary variables	Evaluation criteria
Policy nature (X1)	X1.1 forecast	Whether the policy is predictive, yes 1, no 0
	X1.2 supervise	Whether the policy is regulatory, yes 1, no 0
	X1.3 suggest	Whether the policy is recommendatory, yes 1, no 0
	X1.4 describe	Whether the policy is descriptive, yes 1, no 0
	X1.5 lead	Whether the policy is guided, yes 1, no 0
Policy timeliness (X2)	X2.1 long term	Whether the policy relates to planning beyond 5 years, yes 1, no 0
	X2.2 medium term	Whether the policy relates to 3–5 year planning, yes 1, no 0
	X2.3 short term	Whether the policy relates to 1–3 year planning, yes 1, no 0
Policy level (X3)	X3.1 national level	Whether the policy is issued by a national authority, yes 1, no 0
	X3.2 provincial level	Whether the policy is issued by a provincial or municipal authority, yes 1, no 0
	X3.3 prefecture level	Whether the policy is issued by a local municipal authority, yes 1, no 0
Policy evaluation (X4)	X4.1 sufficient basis	Whether the policy is sufficient basis, yes 1, no 0
	X4.2 clear-cut targets	Whether the objectives of the policy content are clear, yes 1, no 0
	X4.3 Program science	Programmatic science for policy implementation, yes 1, no 0
	X4.4 rational planning	Whether the policy plan is sensible and reasonable, yes 1, no 0
Policy area (X5)	X5.1 economic transformation	Whether the policy involves areas of economic transformation, yes 1, no 0
	X5.2 Government-led	Whether the policy involves areas of government leadership, yes 1, no 0
	X5.3 industry regime	Whether the policy involves the area of industrial regimes, yes 1, no 0
	X5.4 Resource environment	Whether the policy involves the area of resources and environment, yes 1, no 0
	X5.5 green technology	Whether the policy involves the area of green technology, yes 1, no 0
	X5.6 social security	Whether the policy involves the area of social services, yes 1, no 0
Policy guarantee (X6)	X6.1 government subsidy	Whether the policy involves government subsidies, yes 1, no 0
	X6.2 technical support	Whether the policy involves technical support, yes 1, no 0
	X6.3 special fund	Whether the policy involves a special fund, yes 1, no 0
	X6.4 Policies and regulations	Whether the policy involves policies and regulations, yes 1, no 0
	X6.5 talent incentives	Whether the policy involves talent incentives, yes 1, no 0
	X6.6 tax incentives	Whether the policy involves tax incentives, yes 1, no 0
	X6.7 Demonstration projects	Whether the policy involves to demonstration projects, yes 1, no 0
	X6.8 advocacy and education	Whether the policy involves advocacy and education, yes 1, no 0
Policy priority (X7)	X7.1 social governance	Whether the policy involves social governance, yes 1, no 0
	X7.2 digital governance	Whether the policy involves digital governance, yes 1, no 0
	X7.3 infrastructure improvement	Whether the policy involves infrastructure improvements, yes 1, no 0
	X7.4 industrial structure	Whether the policy involves industrial structure, yes 1, no 0
	X7.5 resource exhaustion support	Whether the policy involves resource exhaustion support, yes 1, no 0
	X7.6 industrial transformation	Whether the policy involves industrial transformation, yes 1, no 0
	X7.7 environmental improvement	Whether the policy involves environmental improvement, yes 1, no 0
Policy Object (X8)	X8.1 government branch	Whether the policy is oriented towards the government branch, yes 1, no 0
	X8.2 social enterprise	Whether the policy is oriented towards social enterprises, yes 1, no 0
Policy perspective (X9)	X9.1 macro level	Whether the policy has a macro perspective, yes 1, no 0
	X9.2 micro level	Whether the policy has a micro perspective, yes 1, no 0

Table 5 PMC index of supporting policies.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	PMC	Grade	Ranking
P1	0.600	0.333	0.333	1.000	1.000	0.625	0.857	1.000	1.000	6.749	Good	14
P2	0.800	0.333	0.333	1.000	1.000	0.875	0.857	1.000	1.000	7.199	Excellent	8
P3	0.600	0.333	0.333	1.000	1.000	1.000	1.000	1.000	1.000	7.267	Excellent	7
P4	0.600	0.333	0.333	1.000	1.000	0.625	0.714	1.000	1.000	6.606	Good	15
P5	0.600	0.333	0.333	1.000	1.000	0.875	0.714	1.000	1.000	6.856	Good	13
P6	0.800	0.333	0.333	1.000	1.000	1.000	0.857	1.000	1.000	7.324	Excellent	5
P7	0.800	0.333	0.333	1.000	1.000	0.875	0.857	1.000	1.000	7.199	Excellent	9
P8	0.600	0.333	0.333	1.000	1.000	0.750	0.571	1.000	1.000	6.588	Good	16
P9	1.000	0.333	0.333	1.000	1.000	0.750	0.857	1.000	1.000	7.274	Excellent	6
P10	1.000	0.333	0.333	1.000	1.000	0.750	0.571	1.000	1.000	6.988	Good	12
P11	1.000	0.333	0.333	1.000	1.000	1.000	0.857	1.000	1.000	7.524	Excellent	3
P12	0.800	0.333	0.333	1.000	1.000	0.750	0.857	1.000	1.000	7.074	Excellent	10
P13	1.000	0.333	0.333	1.000	1.000	1.000	0.857	1.000	1.000	7.524	Excellent	4
P14	1.000	0.333	0.333	1.000	1.000	1.000	1.000	1.000	1.000	7.667	Excellent	1
P15	0.800	0.333	0.333	1.000	1.000	0.875	0.714	1.000	1.000	7.056	Excellent	11
P16	1.000	0.333	0.333	1.000	1.000	1.000	1.000	1.000	1.000	7.667	Excellent	1
Mean	0.813	0.333	0.333	1.000	1.000	0.859	0.821	1.000	1.000	7.160	Excellent	–

Note: The scores are the results presented after the calculations have been processed with uniform rounding and retaining 3 valid decimals.

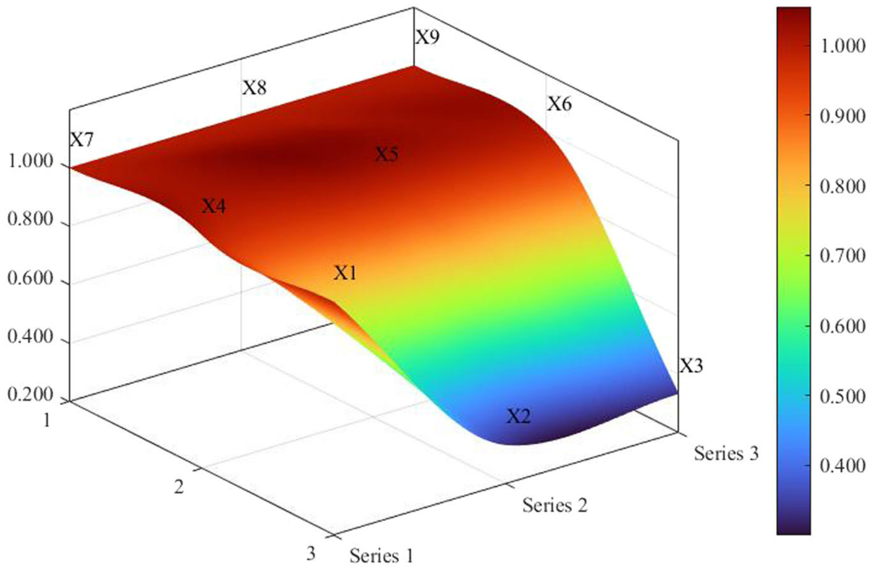

Fig. 2 The PMC surface diagrams of P14.

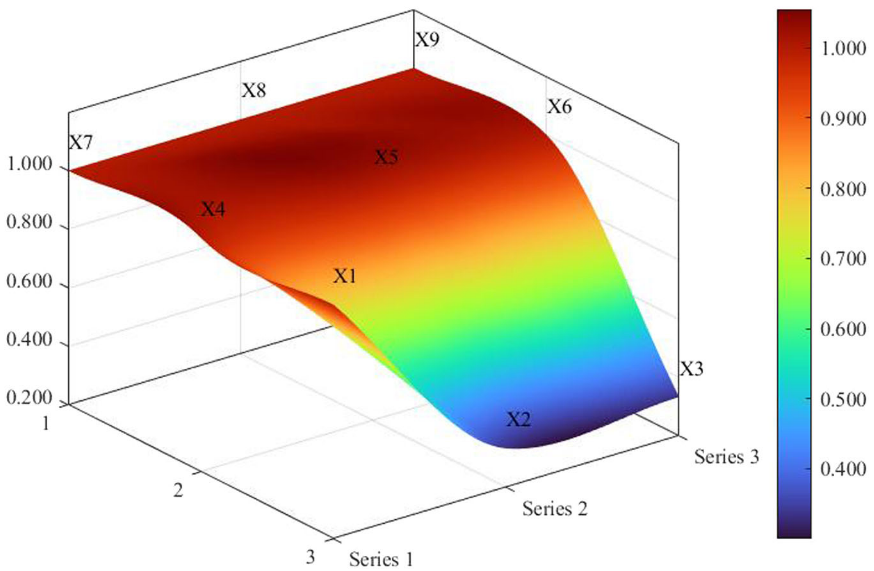

Fig. 3 The PMC surface diagrams of P16.

reverse-proof methodology, which involves contrasting the scores attained by the primary indicators with those of the hypothetical "perfect" policies that achieve maximum scores across all evaluation criteria. The resultant difference between these two scores constitutes the depression index, as exhibited in Table 6. In detail, P8 boasts a depression index of 2.412, which remains a considerable distance from achieving "perfect" policy standards. This signifies that the policy content lacks comprehensiveness, necessitating a sharper focus on optimizing aspects such as X1 (Policy nature), X6 (Policy guarantee), and X7 (Policy priority). It is imperative to provide comprehensive explanations regarding the predictability, oversight, and foresight embedded within the policy content, ensuring alignment with the specific green transformation challenges faced by resource-exhausted cities. Moreover, the successful implementation of green transformation hinges on adequate informational disclosure, monitoring mechanisms, and forward-thinking policy adjustments tailored to the unique circumstances of these cities. Financial support is also crucial, and the strategic introduction of talent and technology, as core drivers of transformation, must be prioritized. This includes enhancing talent development programs and incentive mechanisms to attract and retain skilled individuals. Furthermore, the provision of targeted tax incentives to relevant industries and enterprises is essential to attract innovative and environmentally friendly businesses to these regions. Such measures will significantly contribute to the materialization of green transformation efforts, laying a solid foundation for sustainable development. Besides, the P14 and P16 possess the minimal depression index of 1.333, which approximates the "perfect" policy the closest. The mean depression index of the 16 policies is 1.840, suggesting that the policies generally align with anticipations. Nevertheless, further enhancement is warranted, primarily in refining and adjusting X1 (Policy nature), X6 (Policy guarantee), and X7 (Policy priority). Thereby, it is imperative to prioritize enhancing the feasibility and foresight of policies, to facilitate the green transformation of resource-exhausted cities through financial support and assistance. This will vigorously foster green industries and promote the growth of a green economy.

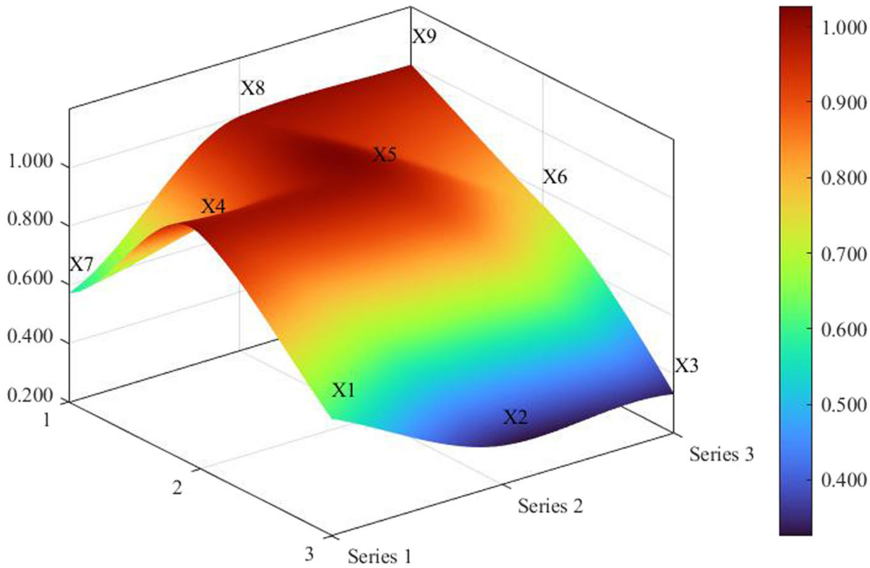

Fig. 4 The PMC surface diagrams of P8.

Table 6 Depression index of supporting policies.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	Depression index	Ranking
P1	0.400	0.667	0.667	0.000	0.000	0.375	0.143	0.000	0.000	2.251	3
P2	0.200	0.667	0.667	0.000	0.000	0.125	0.143	0.000	0.000	1.801	8
P3	0.400	0.667	0.667	0.000	0.000	0.000	0.000	0.000	0.000	1.733	10
P4	0.400	0.667	0.667	0.000	0.000	0.375	0.286	0.000	0.000	2.394	2
P5	0.400	0.667	0.667	0.000	0.000	0.125	0.286	0.000	0.000	2.144	4
P6	0.200	0.667	0.667	0.000	0.000	0.000	0.143	0.000	0.000	1.676	12
P7	0.200	0.667	0.667	0.000	0.000	0.125	0.143	0.000	0.000	1.801	9
P8	0.400	0.667	0.667	0.000	0.000	0.250	0.429	0.000	0.000	2.412	1
P9	0.000	0.667	0.667	0.000	0.000	0.250	0.143	0.000	0.000	1.726	11
P10	0.000	0.667	0.667	0.000	0.000	0.250	0.429	0.000	0.000	2.012	5
P11	0.000	0.667	0.667	0.000	0.000	0.000	0.143	0.000	0.000	1.476	13
P12	0.200	0.667	0.667	0.000	0.000	0.250	0.143	0.000	0.000	1.926	7
P13	0.000	0.667	0.667	0.000	0.000	0.000	0.143	0.000	0.000	1.476	14
P14	0.000	0.667	0.667	0.000	0.000	0.000	0.000	0.000	0.000	1.333	15
P15	0.200	0.667	0.667	0.000	0.000	0.125	0.286	0.000	0.000	1.944	6
P16	0.000	0.667	0.667	0.000	0.000	0.000	0.000	0.000	0.000	1.333	16
Mean	0.187	0.667	0.667	0.000	0.000	0.141	0.179	0.000	0.000	1.840	-

Note: The scores are the results presented after the calculations have been processed with uniform rounding and retaining 3 valid decimals.

Causes identification

Variables calibration and necessary causes analysis. As can be seen from the above, the implementation of relevant supporting policies for resource-exhausted cities has been very recognized and successful, and the elaboration of their content on green development has a positive significance for the green transformation of resource-exhausted cities. The comprehensiveness of policy content and the good implementation of policies provide us with official guidance value for further exploring the green transformation path of resource-exhausted cities. Having policies to rely on is a major feature of China's development model, and this top-down governance model provides a policy premise for us to identify the green transformation paths. Next, based on the good implementation of policies, we will use the fsQCA method to conduct research on the path identification of green transformation in resource-exhausted cities, due to its advantage in identifying the complex configuration mechanisms in limited samples.

Due to the novel nature of the green transformation index for resource-exhausted cities and the measurement of associated causal factors, there is a significant absence of established theoretical delineation standards within the academic realm. Consequently, this study draws upon existing research and employs a direct calibration approach, which utilizes the 95, 50, and 5% quartile of the case samples as anchor points for defining the relationships between antecedent variables and the outcome variable. It can be categorized as affiliation, intersection, and non-affiliation, respectively. Table 7 provides a detailed overview of the specific calibration anchor points and descriptive statistics.

After calibrating the variables, the necessary causes for the green transformation of resource-exhausted cities can be analyzed. The green transformation index of these cities is designated as the outcome variable, while technological innovation, infrastructure development, management mode change, production process improvement, market competition pressure, industrial development level, and support policy combinations

Table 7 Variables calibration and descriptive statistics.

Variables	Variables calibration			Descriptive statistics			
	Non-affiliation	Intersection	Affiliation	Mean	SD	Min	Max
TI	0.143	0.733	3.683	1.231	1.439	0.059	12.959
ID	1.972	7.800	16.483	8.432	5.204	0.765	71.660
MMC	7.746	30.860	93.716	38.782	29.142	2.034	186.882
PPI	2.027	2.220	2.520	2.247	0.148	1.881	2.733
MCP	0.086	1.545	7.845	2.363	2.525	0.000	19.880
IDL	26.563	49.265	67.430	48.262	11.587	18.14	84.880
SPC	0.000	1.000	1.000	0.599	0.490	0.000	1.000
GTI	0.206	0.280	0.527	0.310	0.097	0.139	0.672

Table 8 Analysis of necessary causes.

Causes	Outcome variable			
	Green transformation		~Green transformation	
	Consistency	Coverage	Consistency	Coverage
TI	0.655	0.667	0.592	0.672
~ TI	0.678	0.598	0.707	0.695
ID	0.645	0.627	0.654	0.708
~ ID	0.700	0.645	0.656	0.673
MMC	0.650	0.676	0.559	0.649
~ MMC	0.663	0.574	0.721	0.696
PPI	0.700	0.651	0.647	0.671
~ PPI	0.647	0.622	0.663	0.711
MCP	0.597	0.640	0.593	0.709
~ MCP	0.728	0.617	0.698	0.659
IDL	0.682	0.649	0.671	0.711
~ IDL	0.696	0.655	0.668	0.701
SPC	0.642	0.511	0.553	0.489
~ SPC	0.358	0.418	0.447	0.582

Note: where ~ represents NOT.

Table 9 Combination of causes for green transformation of resource-exhausted cities.

Causes variables	Combination of causes for green transformation					
	L1	L2	L3	L4	L5	L6
TI	⊗	⊗	●	•	⊗	⊗
ID	●	•	⊗	⊗	⊗	⊗
MMC	⊗	⊗	⊗	●	●	⊗
PPI	⊗	●	●	●	⊗	●
MCP	●	⊗	⊗	⊗	●	•
IDL	⊗	⊗	•	⊗	⊗	●
SPC	●	●	●	●	●	●
consistency	0.910	0.895	0.874	0.909	0.910	0.917
Raw coverage	0.157	0.150	0.198	0.192	0.139	0.144
Unique coverage	0.023	0.084	0.012	0.033	0.016	0.018
Solution consistency	0.834					
Solution coverage	0.352					

Notes: ● is the core cause that exists. ⊗ is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

are designated as antecedent variables. The analysis aims to determine whether each antecedent variable independently serves as a necessary factor for green transformation. The results are summarized in Table 8. According to the established criterion, antecedent variables are considered necessary causes if the consistency is 0.9 or above. However, based on the analyzed data, none of the antecedent variables achieved a consistency of 0.9 or above. Consequently, none of the mentioned antecedent variables independently constitutes a necessary factor for influencing the green transformation of resource-exhausted cities.

Combination of causes. Following a thorough necessity analysis, the pertinent parameters were chosen for conditional configuration analysis, tailored to the research objectives. The initial consistency threshold was established at 0.8. Additionally, to minimize the potential for conflicting combinations, a decision was made to elevate the PRI consistency threshold to 0.85. Further, we conduct the heterogeneity analysis from two aspects, including geographical location and resource type. Based on the relevant results in Table 9, the six strategic pathways for the environmentally sustainable transformation of resource-exhausted cities can be outlined.

The first conditional configuration (L1) is ~TI * ID * ~MMC * ~PPI * MCP * ~IDL * SPC. The green transformation of resource-exhausted cities is primarily driven by infrastructure construction, market competition pressure, and the integration of supporting policies. Taking Lvliang and Linfen as illustrative examples, these cities often encounter industrial laggardness due to technological delays, outdated management, and inefficient production processes. Consequently, substantial efforts must be exerted to bolster infrastructure development, refine market mechanisms, and fortify governmental assistance in order to facilitate their green transformation. The second conditional configuration (L2) is ~TI * ID * ~MMC * PPI * ~MCP * ~IDL * SPC. The green transformation of resource-exhausted cities, exemplified by Shizuishan City and Jingdezhen City, is primarily driven by infrastructure construction, process improvement, and the integration of supporting policies. The third conditional configuration (L3) is TI * ~ID * ~MMC * PPI * ~MCP * IDL * SPC. It is evident that technological innovation, enhancement of production processes, the degree of industrial development, and the integration of supporting policies are the primary catalysts for green transformation in cities that have exhausted their natural resources, with Shijiazhuang City and Fushun City serving as representative examples. These cities possess a substantial level of technological advancement and innovation, along with a high level of industrialization and refined production processes. When coupled with the assistance and direction provided by policies, these factors will facilitate the green transformation of these cities. The fourth conditional configuration (L4) is TI * ~ID * MMC * PPI * ~MCP * ~IDL * SPC. The green transformation of resource-exhausted cities, exemplified by Lanzhou City and Chengde City, is primarily driven by technological innovation, market competition pressure, production process improvement,

Table 10 Analysis of regional heterogeneity.

Causes variables	Combination of causes for green transformation								
	Eastern			Middle			Western		
	E1	E2	E3	M1	M2	M3	W1	W2	W3
TI	●	•	●	⊗	●	⊗	•	⊗	⊗
ID	⊗	⊗	●	●	**⊗**	•	●	⊗	●
MMC	•	**⊗**	⊗	**⊗**	●	●	⊗	●	⊗
PPI	●	●	●	●	●	●	**⊗**	•	•
MCP	●	●	●	⊗	●	**⊗**	●	●	**⊗**
IDL	**⊗**	•	●	•	⊗	•	•	⊗	●
SPC	•	**⊗**	●	●	●	•	•	●	•
Consistency	0.879	0.880	0.885	0.909	0.912	0.894	0.946	0.929	0.920
Raw coverage	0.169	0.171	0.167	0.262	0.130	0.133	0.256	0.336	0.152
Unique coverage	0.086	0.052	0.017	0.033	0.121	0.115	0.175	0.255	0.075
Solution consistency	0.837			0.936			0.903		
Solution coverage	0.461			0.474			0.552		

Notes: ● is the core cause that exists. **⊗** is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

and support policy combinations. Technological innovation not only enhances production processes but also plays a pivotal role in optimizing the market environment and fostering healthy market competition. The integration of green technologies into production processes not only minimizes energy consumption but also mitigates pollutant emissions. That is, to some extent, environmental pressure translates into market pressure, prompting improvements and refinements in production processes within industries. The fifth conditional configuration (L5) is ~TI * ~ID * MMC * ~PPI * MCP * ~IDL * SPC. The green transformation of resource-exhausted cities, such as Laibin City and Shaoguan City, is primarily driven by changes in management mode, market competition pressure, and combinations of supporting policies. These cities prioritize the management of industrial production in enterprises, aiming to enhance efficiency through management mode changes, thereby improving market competitiveness. Additionally, a robust management system is essential for monitoring resource consumption and ensuring that production waste meets established standards. Notably, strong policy support serves as a directional force, effectively facilitating green transformation. The sixth conditional configuration (L6) is ~TI * ~ID * ~MMC * PPI * MCP * IDL * SPC. It is proposed that the primary catalysts for promoting the green transformation of resource-exhausted cities, exemplified by Tonghua City and Hengyang City, are the enhancement of production processes, the pressure stemming from market competition, the level of industrial development, and the integration of supporting policies. The advancement of production technology and the refinement of production processes can significantly decrease the rate of energy loss. Furthermore, with the government's promotion and public participation in environmental governance, enterprises, and industries will escalate their investments in green technology research and development. By applying green technology to industrial development and transformation, the green transformation of resource-exhausted cities can be achieved.

The examination of relationships spanning distinct regions uncovers disparities in the channel toward green transformation in resource-exhausted cities. Consequently, this subsection classified the samples based on the cities' geographical locations to delve deeper into the possible heterogeneity. The results are shown in Table 10. In the eastern region, the green transformation of resource-exhausted cities primarily depends on technological advancements and improvements in production processes. These cities leverage their advantageous geographical locations to prioritize innovative technological advancements and cutting-edge production concepts, which are conducive to enhancing production efficiency in the region without compromising environmental standards, thereby laying a solid foundation for the orderly advancement of subsequent green transformation. In comparison, the green transformation of resource-exhausted cities in the central region heavily relies on the profound upgrading of traditional production processes. And the effective establishment and implementation of a supporting policy system also play an indispensable role. For instance, by continuously refining production processes and introducing suitable clean technologies, the cities in this region can effectively transform from resource-dependent models to green, sustainable development paradigms. As for the Western region, given the geographical constraints, the focus on promoting the green transformation of resource-exhausted cities tends to emphasize infrastructure development and supporting policies, particularly the imperative construction of transportation networks. Meanwhile, guiding the allocation of economic resources through rational policies is crucial for fostering sustainable development.

Furthermore, to explore the differences in the process of green transformation among resource-exhausted cities with different resource types, the resource types are classified into coal, oil, metal, and forestry and others, in accordance with the Notice on the National Sustainable Development Plan for Resource-Based Cities (2013–2020) issued by the State Council. Then, an analysis is conducted based on the resource classification, and the results are presented in detail in Table 11. Regarding coal and oil resource-exhausted cities, the achievement of green transformation mostly relies on the macro-leading and theoretical guidance of government policies, combined with technological innovation in related industries, to carry out large-scale adjustments to the industrial structure. Meanwhile, the increased market competition pressure due to the direct investment of foreign capital in the domestic market has forced domestic resource-based industries to quickly achieve green transformation. Conversely, the green transformation of metal, forestry and other resource-exhausted cities relies on the upgrading and advancement of the industrial structure. Simultaneously, relevant policies are used to guide and direct, with technological innovation as the driving force and the improvement of management structure as a supporting condition, ultimately promoting green transformation.

It cannot be denied that the administrative level of cities, innovation capabilities, and distance to provincial capital cities can

Table 11 Analysis of resource type heterogeneity.

Causes variables	Combination of causes for green transformation							
	Coal		Oil		Metal		Forestry and others	
	C1	C2	O1	O2	M1	M2	F1	F2
TI	•	⊗	●	●	•	•	⊗	•
ID	⊗	•	⊗	⊗	⊗	⊗	⊗	⊗
MMC	•	⊗	•	•	⊗	⊗	•	•
PPI	⊗	⊗	•	•	●	●	●	●
MCP	•	•	•	⊗	⊗	•	⊗	⊗
IDL	⊗	⊗	⊗	⊗	⊗	•	•	•
SPC	●	●	●	●	•	⊗	•	•
Consistency	0.930	0.911	0.889	0.888	0.879	0.843	0.900	0.899
Raw coverage	0.142	0.159	0.253	0.219	0.227	0.296	0.274	0.383
Unique coverage	0.001	0.017	0.019	0.029	0.012	0.013	0.037	0.019
Solution consistency	0.853		0.827		0.780		0.811	
Solution coverage	0.301		0.580		0.688		0.769	

Notes: ● is the core cause that exists. ⊗ is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

Table 12 Analysis of city administrative level heterogeneity.

Causes variables	Combination of causes for green transformation							
	Prefecture-level city				Non-prefecture-level city			
	P1	P2	P3	P4	NP1	NP2	NP3	NP4
TI	●	•	●	⊗	•	⊗	⊗	•
ID	⊗	•	⊗	⊗	⊗	•	•	•
MMC	⊗	⊗	⊗	•	⊗	•	•	•
PPI	⊗	⊗	•	•	●	⊗	●	⊗
MCP	•	•	⊗	⊗	⊗	•	•	⊗
IDL	•	⊗	•	•	⊗	⊗	•	⊗
SPC	●	●	•	●	●	•	⊗	⊗
Consistency	0.878	0.881	0.883	0.886	0.879	0.877	0.895	0.914
Raw coverage	0.225	0.197	0.213	0.220	0.223	0.170	0.220	0.218
Unique coverage	0.001	0.012	0.011	0.019	0.047	0.016	0.019	0.018
Solution consistency	0.832				0.777			
Solution coverage	0.502				0.637			

Notes: ● is the core cause that exists. ⊗ is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

all affect the green transformation of resource-exhausted cities. To more precisely identify feasible paths for the green transformation of resource-exhausted cities, the city samples were divided into three groups: the first is prefecture-level cities and non-prefecture-level cities, the second is high-innovation and low-innovation capabilities, and the third is cities located more than 200 km and less than 200 km from provincial capital cities. Table 12 clearly demonstrates the paths for achieving green transformation in resource-exhausted cities, categorized by the administrative level of cities. Due to their higher administrative level, prefecture-level cities have easier access to technological and managerial resources, a more advanced industrial structure, and the support of relevant policies, which all facilitate green transformation. In contrast, non-prefecture-level resource-exhausted cities rely more on local infrastructure and distinctive industries for green transformation, with few receiving timely policy support. In terms of innovation capabilities, Table 13 clearly shows that cities with high innovation capabilities tend to rely more on enhancing technological innovation, increasing market competitiveness, and promoting industrial upgrading to achieve green transformation, with lower dependence on supporting policies. Conversely, cities with low innovation capabilities rely more on national supporting policies and local distinctive industries to promote green innovation. Theoretically, cities closer to provincial capital cities are more likely to benefit from their radiation effects, accelerating green transformation. The results presented in Table 14 confirm this view. Cities located more than 200 km from provincial capital cities cannot efficiently and timely absorb resources from these cities and must rely on local industrial structural transformation and relevant support policies for green transformation. Cities within 200 km of provincial capital cities, however, enjoy the advantage of proximity, enabling them to access technological, managerial, and advanced industrial models from regional hub cities. With the support of policies, target cities can efficiently and effectively achieve green transformation.

Conclusions, policy implications, and research prospect

Conclusions. This study employs the PMC index model to conduct an in-depth analysis of the implementation effectiveness of support policies for resource-exhausted cities at both central and local levels. Additionally, using the fsQCA method, it explores the interaction mechanisms and effects of various internal and external factors in the context of policy coordination as these cities pursue green transformation, relying on the panel data from 56 resource-exhausted cities spanning from 2003 to 2018. These factors encompass organizational, technological, environmental, and policy conditions. The findings reveal that the overall effectiveness of these

Table 13 Analysis of urban innovation capacity heterogeneity.

Causes variables	Combination of causes for green transformation							
	High innovation capacity				Low innovation capacity			
	IH1	IH2	IH3	IH4	IL1	IL2	IL3	IL4
TI	•	●	•	•	⊗	⊗	⊗	⊗
ID	⊗	⊗	⊗	⊗	⊗	⊗	•	⊗
MMC	•	⊗	⊗	⊗	•	•	⊗	⊗
PPI	⊗	⊗	⊗	⊗	●	⊗	⊗	⊗
MCP	⊗	•	•	•	⊗	•	•	⊗
IDL	⊗	•	•	•	⊗	•	⊗	●
SPC	●	•	⊗	⊗	•	•	●	•
Consistency	0.838	0.857	0.900	0.892	0.820	0.922	0.857	0.848
Raw coverage	0.347	0.295	0.274	0.294	0.191	0.091	0.098	0.150
Unique coverage	0.047	0.035	0.019	0.027	0.024	0.004	0.017	0.034
Solution consistency	0.801				0.814			
Solution coverage	0.632				0.435			

Notes: ● is the core cause that exists. ⊗ is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

Table 14 Analysis of distance to provincial capital heterogeneity.

Causes variables	Combination of causes for green transformation							
	Over 200 km				Under 200 km			
	O1	O2	O3	O4	U1	U2	U3	U4
TI	⊗	•	⊗	⊗	●	•	⊗	•
ID	•	⊗	⊗	•	⊗	⊗	⊗	⊗
MMC	⊗	⊗	•	⊗	•	•	•	•
PPI	•	•	•	•	⊗	●	•	⊗
MCP	⊗	⊗	•	⊗	⊗	•	⊗	•
IDL	●	⊗	●	•	•	⊗	⊗	⊗
SPC	⊗	●	•	●	•	•	●	●
Consistency	0.891	0.860	0.879	0.876	0.885	0.889	0.896	0.895
Raw coverage	0.119	0.229	0.168	0.184	0.068	0.185	0.191	0.179
Unique coverage	0.011	0.050	0.011	0.022	0.068	0.072	0.016	0.020
Solution consistency	0.842				0.837			
Solution coverage	0.476				0.468			

Notes: ● is the core cause that exists. ⊗ is the core cause missing. • is the edge cause that exists. ⊗ is the edge cause missing.

supporting policies is commendable, exhibiting a pattern of "superior quality at lower administrative levels". Furthermore, the green transformation of resource-exhausted cities relies on the harmonious integration of multiple factors rather than any single condition. From the perspective of regional differences, the green transformation of resource-exhausted cities in eastern region primarily depends on technological advancements and production process improvements, the central region leans toward production process enhancements and a blend of supporting policies, while the western region relies heavily on infrastructure development and a combination of supporting policies. Then, from the perspective of resource type, the green transformation of resource-exhausted cities, particularly those reliant on coal and petroleum, heavily depends on the macro-leading and theoretical guidance of government policies, combined with technological innovations in related industries, to achieve large-scale adjustments in industrial structure. The green transformation of metal, forestry and other types of resource-exhausted cities relies on the upgrading and advancement of industrial structure. In a collective examination of administrative level, innovation capability, and distance to the provincial capital city, cities with higher administrative levels, higher innovation capabilities, and closer proximity to the provincial capital city are more inclined to undergo green transformation.

Policy implications. While the general implementation of supporting policies has proven effective, it must be acknowledged that this effectiveness may not be uniform across all cities facing resource exhaustion. Given the diverse geographical locations and varying stages of development among cities, coupled with the different degrees of resource depletion, it is imperative to formulate tailored, effective, and feasible support policies. Specifically, in the eastern region, it is imperative to promote green technological innovation to reduce reliance on traditional resources. In the central region, efforts must be intensified to improve production processes and reduce energy consumption. Besides, in the western region, where development remains relatively underdeveloped, a stronger focus should be placed on infrastructure construction to lay a solid foundation for the sustainable development of resource-exhausted cities. In terms of different resource types, it is necessary to provide quality policy support for resource-exhausted cities relying on coal and oil, increase investment in technological innovation, and advocate the popularization and promotion of green and clean technologies. Meanwhile, for metal, forestry, and other types of resource-exhausted cities, it is important to provide valuable industrial restructuring models, encourage the research, development, and introduction of high-tech equipment, and vigorously promote green transformation. For those resource-exhausted cities with low administrative levels, weak innovation capabilities, and far distances from provincial capitals, more attention and care should be given, and policy support should be strengthened. Relying on the city's own advantages promotes the realization of green transformation.

Moreover, the successful green transformation of resource-exhausted cities hinges crucially on the collaborative efforts of various departments, thereby ensuring the efficient implementation of policies. That is, it is imperative for the government to enhance the market environment, bolster financial assistance, and offer favorable external conditions and funding support to facilitate the green transformation and upgrading of enterprises. It is incumbent upon each enterprise to align with government directives, proactively recruit high-tech talents, vigorously pursue the development of green technologies, and minimize dependence on traditional resources in their operational processes. The concurrent commitment of the government, enterprises, and the general public holds the key to achieving effective transformation in resource-exhausted cities.

Lastly, regarding the optimization of the content of existing policies, emphasis should be placed on policy nature, policy guarantee, and policy priority. Comprehensive explanations must be provided for the predictability, supervision, and foresight embedded in the policy content to ensure alignment with the specific green transformation challenges faced by resource-exhausted cities. Furthermore, the successful implementation of green transformation hinges on adequate information disclosure, monitoring mechanisms, and proactive policy adjustments tailored to the unique environments of these cities. Financial support is also crucial, with a priority on talent and technology as the core driving factors for transformation. This includes strengthening talent development plans and incentive mechanisms to attract and retain skilled individuals. Additionally, targeted tax incentives for relevant industries and enterprises are vital to attracting innovative and environmentally friendly businesses to these regions. Simultaneously, policies should guide local industries to undergo green transformation, improve quality and efficiency, and advocate the use of green technologies and clean energy, with development as the goal, green concepts as the orientation, and industrial transformation as the carrier to promote the green transformation of resource-exhausted cities. These measures will significantly contribute to the efforts towards green transformation, laying a solid foundation for the sustainable development of these cities.

Research prospect. Although the study makes certain marginal contributions to existing research, it still has the following issues that need improvement. Firstly, this research is limited by its focus on a specific type of city, which may not fully capture the broader dynamics of urban green transition across different contexts. Future research can extend beyond resource-exhausted cities to explore sustainable development models on a broader scale. Such panoramic studies can help extract universally applicable transition principles and strategies, encompassing not only resource-rich cities seeking preventive transformation but also non-resource-dependent cities aiming for harmonious economic, social, and environmental coexistence under sustainable development goals. Additionally, this approach can identify similarities and differences in transformation paths among different city types, providing a basis for formulating more precise policies. Secondly, the issues of methodological constraints. With continuous advancements in data science and analytical techniques, future research should actively adopt advanced methods to identify key influencing factors and their interaction mechanisms more accurately in the transition process. For instance, the structure equation model (SEM) can help establish complex causal relationship models, analyzing how factors like technology adoption, organizational change, and policy environment jointly influence the process of urban green transition. Besides, the machine learning method can be used for large-scale data mining to analyze the potential impact and effectiveness of related policies more comprehensively.

Data availability

The datasets generated during and/or analyzed during the current study are not publicly available because they are subject to third-party restrictions.

Received: 26 March 2024; Accepted: 11 October 2024;
Published online: 19 October 2024

References

Ahmadova G, Delgado-Márquez BL, Pedauga LE, Leyva-de la Hiz DI (2022) Too good to be true: The inverted U-shaped relationship between home-country digitalization and environmental performance. Ecol Econ 196:107393. https://doi.org/10.1016/j.ecolecon.2022.107393

Awan AG (2013) Relationship between environment and sustainable economic development: a theoretical approach to environmental problems. Int J Asian Soc Sci 3(3):741–761

Bei J (2018) Study on the "high-quality development" economics. China Ind Econ 1(2):163–180. https://doi.org/10.1108/CPE-10-2018-016

Chen H, Wu H, Zhang L, Tang Y, Lu S (2024) Does green financial policy promote the transformation of resource-exhausted cities?—evidence from the micro level. Resour Policy 88:104500. https://doi.org/10.1016/j.resourpol.2023.104500

Chen W, Shen Y, Wang Y (2018) Evaluation of economic transformation and upgrading of resource-based cities in Shaanxi province based on an improved TOPSIS method. Sustain Cities Soc 37:232–240. https://doi.org/10.1016/j.scs.2017.11.019

Dewulf J, Benini L, Mancini L, Sala S, Blengini GA, Ardente F, Pennington D (2015) Rethinking the area of protection "natural resources" in life cycle assessment. Environ Sci technol 49(9):5310–5317. https://doi.org/10.1021/acs.est.5b00734

Dou Q, Gao X (2023) How does the digital transformation of corporates affect green technology innovation? An empirical study from the perspective of asymmetric effects and structural breakpoints. J Clean Prod 428:139245. https://doi.org/10.1016/j.jclepro.2023.139245

Dou S, Zhu Y, Xu D, Amuakwa-Mensah F (2023) Ecological challenges in the economic recovery of resource-exhausted cities in China. J Environ Manag 333:117406. https://doi.org/10.1016/j.jenvman.2023.117406

Dreyer JT (2018) China's political system: modernization and tradition. Routledge. https://doi.org/10.4324/9781315144399

Ebhota WS, Jen TC (2020) Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system. Int J Precis Eng Manuf Green Tech 7:97–117. https://doi.org/10.1007/s40684-019-00101-9

Guo L, Qu Y, Wu C et al. (2018) Identifying a pathway towards green growth of Chinese industrial regions based on a system dynamics approach. Resour Conserv Recycl 128:143–154. https://doi.org/10.1016/j.resconrec.2016.09.03

Haibo X, Ahmad A, Phuoc JC, Baogui W (2023) College gymnasium under the teaching background. Int J Multidiscip Res Stud 5:12. https://doi.org/10.33826/ijmras/v05i12.1

He Z, Feng J, Luo J & Zeng Y (2023) Distribution, exploitation, and utilization of intermediate-to-deep geothermal resources in eastern China. Energy Geosci. https://doi.org/10.1016/j.engeos.2023.100187

Hou J, Teo TS, Zhou F, Lim MK, Chen H (2018) Does industrial green transformation successfully facilitate a decrease in carbon intensity in China? An environmental regulation perspective. J Clean Prod 184:1060–1071. https://doi.org/10.1016/j.jclepro.2018.02.311

Huarng KH (2016) Identifying regime switches using causal recipes. J Bus Res 69(4):1498–1502. https://doi.org/10.1016/j.jbusres.2015.10.131

Jahanger A, Usman M, Murshed M, Mahmood H, Balsalobre-Lorente D (2022) The linkages between natural resources, human capital, globalization, economic growth, financial development, and ecological footprint: The

moderating role of technological innovations. Resour Policy 76:102569. https://doi.org/10.1016/j.resourpol.2022.102569
Kalair A, Abas N, Saleem MS, Kalair AR, Khan N (2021) Role of energy storage systems in energy transition from fossil fuels to renewables. Energy Storage 3(1):e135. https://doi.org/10.1002/est2.135
Karpenko L, Izha M, Verbitsky D, Burdeinyi O (2023) International Retrospective of the Anti-Corruption Standards Development in the Economic Security System of Ukraine. J Public Policy Adm USA 7(1):18–24. https://doi.org/10.11648/j.jppa.20230701.13
Khan S, Haneklaus N (2023) Sustainable economic development across globe: the dynamics between technology, digital trade and economic performance. Technol Soc 72:102207. https://doi.org/10.1016/j.techsoc.2023.102207
Khasawneh M (2024) Beyond digital platforms: gamified skill development in real-world scenarios and environmental variables. Int J Data Netw Sci 8(1):213–220. https://doi.org/10.5267/j.ijdns.2023.10.002
Kuang B, Han J, Lu X, Zhang X, Fan X (2020) Quantitative evaluation of China's cultivated land protection policies based on the PMC-Index model. Land Use Policy 99:105062. https://doi.org/10.1016/j.landusepol.2020.105062
Liu E, Wang Y, Chen W et al. (2021) Evaluating the transformation of China's resource-based cities: an integrated sequential weight and TOPSIS approach. Socio-Econ Plan Sci 77:101022. https://doi.org/10.1016/j.seps.2021.101022
Li H, Long R, Chen H (2013) Economic transition policies in Chinese resource-based cities: an overview of government efforts. Energ Policy 55:251–260. https://doi.org/10.1016/j.enpol.2012.12.007
Li M, Liu J, Chen Y, Yang Z (2023) Can sustainable development strategy reduce income inequality in resource-based regions? A natural resource dependence perspective. Resour Policy 81:103330. https://doi.org/10.1016/j.resourpol.2023.103330
Liang S, Tan Q (2024) Can the digital economy accelerates China's export technology upgrading? Based on the perspective of export technology complexity. Technol Forecast Soc 199:123052. https://doi.org/10.1016/j.techfore.2023.123052
Luo K, Liu Y, Chen PF, Zeng M (2022) Assessing the impact of digital economy on green development efficiency in the Yangtze River Economic Belt. Energ Econ 112:106127. https://doi.org/10.1016/j.eneco.2022.106127
Luttropp C, Lagerstedt J (2006) EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. J Clean Prod 14(15-16):1396–1408. https://doi.org/10.1016/j.jclepro.2005.11.022
Lv C, Shao C, Lee CC (2021) Green technology innovation and financial development: do environmental regulation and innovation output matter? Energ Econ 98:105237. https://doi.org/10.1016/j.eneco.2021.105237
Maddikunta PKR, Pham QV, Prabadevi B, Deepa N, Dev K, Gadekallu TR, Liyanage M (2022) Industry 5.0: a survey on enabling technologies and potential applications. J Ind Inf Integr 26:100257. https://doi.org/10.1016/j.jii.2021.100257
Mendel JM, Korjani MM (2013) Theoretical aspects of fuzzy set qualitative comparative analysis (fsQCA). Inform Sci 237:137–161. https://doi.org/10.1016/j.ins.2013.02.048
Pearce DW & Turner RK (1989) Economics of natural resources and the environment. Johns Hopkins University Press
Peng C, Jia X, Zou Y (2023) Can "splitting" be beneficial? The impact of top management team information-knowledge faultline on enterprise green transformation. J Clean Prod 406:136935. https://doi.org/10.1016/j.jclepro.2023.136935
Pollard J, Osmani M, Grubnic S, Díaz AI, Grobe K, Kaba A, Panchal R (2023) Implementing a circular economy business model canvas in the electrical and electronic manufacturing sector: a case study approach. Sustain Prod Consum 36:17–31. https://doi.org/10.1016/j.spc.2022.12.009
Ruan F, Yan L, Wang D (2020) The complexity for the resource-based cities in China on creating sustainable development. Cities 97:102571. https://doi.org/10.1016/j.cities.2019.102571
Shen Q, Pan Y, Meng X, Ling X, Hu S, Feng Y (2023) How does the transition policy of mineral resource-exhausted cities affect the process of industrial upgrading? New empirical evidence from China. Resour Policy 86:104226. https://doi.org/10.1016/j.resourpol.2023.104226
Shi R, Gao P, Su X, Zhang X, Yang X (2024) Synergizing natural resources and sustainable development: a study of industrial structure, and green innovation in Chinese region. Resour Policy 88:104451. https://doi.org/10.1016/j.resourpol.2023.104451
Shan S, Genç SY, Kamran HW et al. (2021) Role of green technology innovation and renewable energy in carbon neutrality: a sustainable investigation from Turkey. J Environ Manag 294:113004. https://doi.org/10.1016/j.jenvman.2021.113004
Sun Z, Zhang J (2022) Impact of resource-saving and environment-friendly society construction on sustainability. Sustainability 14(18):11139. https://doi.org/10.3390/su141811139
Song M, Cen L, Zheng Z, Fisher R, Liang X, Wang Y, Huisingh D (2017) How would big data support societal development and environmental sustainability? Insights and practices. J Clean Prod 142:489–500. https://doi.org/10.1016/j.jclepro.2016.10.091
Song Y, Yang L, Sindakis S, Aggarwal S, Chen C (2023) Analyzing the role of high-tech industrial agglomeration in green transformation and upgrading of manufacturing industry: the case of China. J Knowl Econ 14(4):3847–3877. https://doi.org/10.1007/s13132-022-00899-x
Uralovich KS, Toshmamatovich TU, Kubayevich KF, Sapaev IB, Saylaubaevna SS, Beknazarova ZF, Khurramov A (2023) A primary factor in sustainable development and environmental sustainability is environmental education. Casp J Environ Sci 21(4):965–975. https://doi.org/10.22124/cjes.2023.7155
Wang F, Wang R, He Z (2021) The impact of environmental pollution and green finance on the high-quality development of energy based on spatial Dubin model. Resour Policy 74:102451. https://doi.org/10.1016/j.resourpol.2021.102451
Wang K, Chen X, Wang C (2023) The impact of sustainable development planning in resource-based cities on corporate ESG–evidence from China. Energ Econ 127:107087. https://doi.org/10.1016/j.eneco.2023.107087
Wang R, Wang F (2022) Exploring the role of green finance and energy development towards high-quality economic development: application of spatial Durbin model and intermediary effect model. Int J Env Res Public Health 19(14):8875. https://doi.org/10.3390/ijerph19148875
Wang Y, Chen H, Long R et al. (2022) Has the sustainable development planning policy promoted the green transformation in China's resource-based cities? Resour Conserv Recycl 180:106181. https://doi.org/10.1016/j.resconrec.2022.106181
Wu G, Gao Y, Feng Y (2023) Assessing the environmental effects of the supporting policies for mineral resource-exhausted cities in China. Resour Policy 85:103939. https://doi.org/10.1016/j.resourpol.2023.103939
Wu Y (2000) Is China's economic growth sustainable? A productivity analysis. China Econ Rev 11(3):278–296. https://doi.org/10.1016/S1043-951X(00)00022-5
Yahman Y, Setyagama A (2023) Government policy in regulating the environment for development of sustainable environment in Indonesia. Environ Dev Sustain 25(11):12829–12840. https://doi.org/10.1007/s10668-022-02591-1
Yang Y, Guo H, Chen L, Liu X, Gu M, Ke X (2019) Regional analysis of the green development level differences in Chinese mineral resource-based cities. Resour Policy 61:261–272. https://doi.org/10.1016/j.resourpol.2019.02.003
Yang W, Wang MR (2023) Environmental regulation and green technology innovation: incentive or disincentive effect? New evidence from resource-based cities in China. Environ Sci Pollut Res 30(12):34440–34459. https://doi.org/10.1007/s11356-022-24185-0
Yang Z, Cao Y, Du J (2023) The impact of new urbanization construction on sustainable economic growth of resource-based cities. Environ Sci Pollut Res 30(43):96860–96874. https://doi.org/10.1007/s11356-023-29171-8
Yu J, Yao S, Chen R et al. (2005) A quantitative integrated evaluation of sustainable development of mineral resources of a mining city: a case study of Huangshi, Eastern China. Resour Policy 30(1):7–19. https://doi.org/10.1016/j.resourpol.2004.08.006
Zhai X, An Y (2020) Analyzing influencing factors of green transformation in China's manufacturing industry under environmental regulation: a structural equation model. J Clean Prod 251:119760. https://doi.org/10.1016/j.jclepro.2019.119760
Zhao X, Jiang M, Wu Z, Zhou Y (2023) Quantitative evaluation of China's energy security policy under the background of intensifying geopolitical conflicts: based on PMC model. Resour Policy 85:104032. https://doi.org/10.1016/j.resourpol.2023.104032
Zhu Y, Luo Y, Chen J, Wan Q (2023) Industrial transformation efficiency and sustainable development of resource-exhausted cities: a case study of Daye City, Hubei province, China. Env Dev Sustain 1–25. https://doi.org/10.1007/s10668-023-03269-y
Zhang H, Xiong L, Li L et al. (2018) Political incentives, transformation efficiency and resource-exhausted cities. J Clean Prod 196:1418–1428. https://doi.org/10.1016/j.jclepro.2018.06.093

Acknowledgements

We acknowledge the financial support from the National Natural Science Foundation of China (72404249), the Key Research and Special Popularization (Soft Science Research) Projects of Henan Province (242400411074), and the New Interdisciplinary Training Program of Digital Economy and Industrial Innovation in Zhengzhou University (2024-SSY-GFXL-005).

Author contributions

Conceptualization, Yanchao Feng; Methodology, Yue Gao; Software, Yanchao Feng; Validation, Yue Gao; Formal analysis, Yue Gao and Yuxi Pan; Data curation, Yue Gao;

Writing—original draft preparation, Yue Gao; Writing—review and editing, Yuxi Pan; Visualization, Yanchao Feng; Supervision, Yuxi Pan; Funding acquisition, Yanchao Feng.

Competing interests
The authors declare no competing interests.

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

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

Additional information
Correspondence and requests for materials should be addressed to Yuxi Pan.