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Research Paper

Impact of natural resource mining on sustainable economic development: The role of education and green innovation in China

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ABSTRACT

As the extraction and usage of natural resources continue to be a double-edged sword – supporting economic growth but deteriorating the environment- we study the impact of natural resource mining on sustainable economic development in the largest (PPP) economy – China. We use province-level data from 2001 to 2020 and employ econometric panel techniques, such as fixed effects, two-stage least squares, and a battery of robustness tests. We further explore the potential effects of education and green innovation in mitigating/exacerbating the role of natural resources in the Chinese provincial economy. The results show that: (1) Natural resource mining hurts sustainable development, verifying the "resource curse" effect. (2) Green innovation and education restrain the negative impact of resource mining on sustainable development, turning the curse into a blessing. (3) A regional heterogeneity is observed in the impact of resource mining on sustainable development, showing more significant effects in the Western and low-urbanized regions. (4) Green innovation and education can assuage the curse effect of natural resources into gospel effect. Policy implications and recommendations are proposed in light of the findings to promote sustainable economic development in China.

1. Introduction

Energy and combustion-related CO_2 emissions reached a massive and the highest ever 36.3 Gigatonnes in 2021, recording a 6% increase from the previous year globally. This significant increase in energy use comprised 40% from coal only, which recorded the highest value ever, surpassing the prior peak of 2014 (https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2). China single-handedly accounted for a significant portion of the increase in emissions from the heat and electricity sectors. Although renewable electricity output was at the highest level, most of the massive increase in electricity demand was met with coal-fired power plants (56% of the total growth)(https://www.iea.org/reports/coal-fired-electricity). This clearly shows that global economic development and recovery from the pandemic have not been sustainable but primarily dependent on natural resource usage. Although emissions rose in the US and Europe, but remained lower than pre-pandemic levels (https://www.eia.gov/todayinenergy/detail.php?id=52380). In China, however, it surpassed the pre-COVID-19 levels in 2021. Fig. 1 and Fig. 2 show energy (from natural resources like coal, oil, and gas) production and consumption in China from 2001 to 2020. We can see that coal has consistently remained the largest source of energy production and consumption, raising carbon emissions. As the massive usage of natural resources like coal, gas, and oil is challenging climate goals, there is a need to find ways to mitigate these harmful effects.

China has undergone enormous economic development in the last few decades, resulting in a massive poverty reduction. Chinese economic and social achievements have been remarkable throughout this period (Ma et al., 2022). However, to a large extent, Chinese development lacked renewable and sustainable practices (Iqbal et al., 2022a). This led the Chinese economy to face a severe

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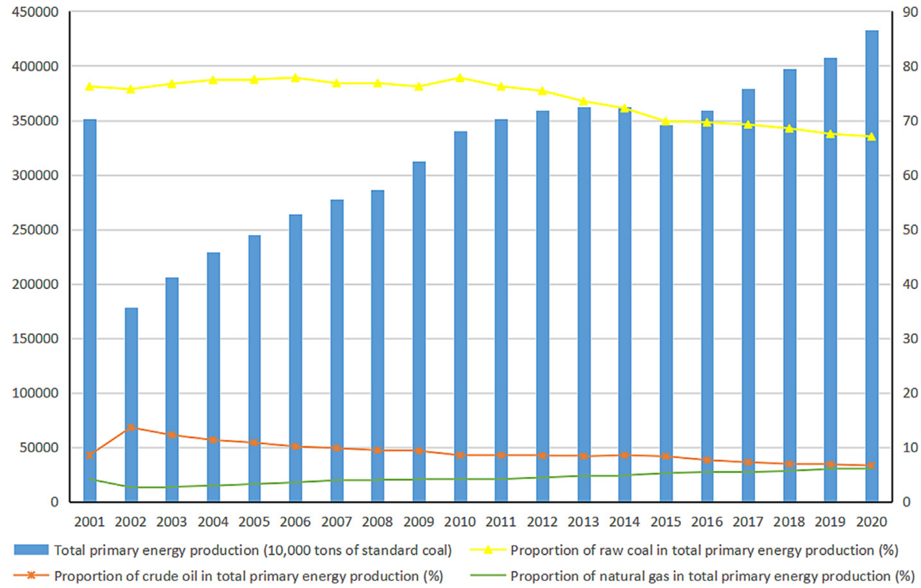

Fig. 1. Primary energy production from 2001 to 2020.

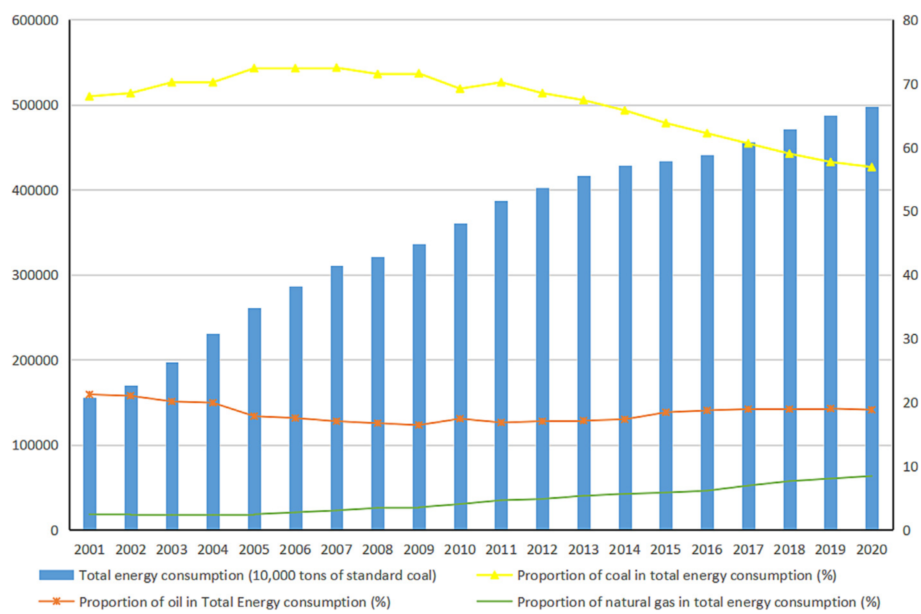

Fig. 2. Total energy consumption from 2001 to 2020.

natural resource shortage, adding to existing challenges to sustainable economic development (Song et al., 2019). Over the past five decades, global economic development has been out of balance compared to sustainable development practices, resulting in high resource consumption and severe environmental degradation (for example, Pan et al., 2019; Wang and Song, 2014). However, due to the high demand from traditional industries for energy resources and old industrial practices, this situation cannot be changed in the short run (Chen and Delmas, 2012). Therefore, policymakers must implement long-term sustainable practices that help support economies meeting the UN sustainable development goals by 2030 (Iqbal et al., 2022b). A recent World Bank report shows that 75% of total greenhouse gas comprises CO_2 from various economic development activities (World Bank, 2021). For example, high carbon-intensive industrial production is pursued by corporate management in order to maximize shareholders' profits. Therefore, corporate management and national governments must take sustainable actions that help reduce CO_2 emissions in line with UNSDGs (Ma et al., 2021). Hossain et al. (2022) highlight the importance of sustainable factors to minimize environmental pollution, especially in countries with abundant national resources.

Besides increasing the energy efficiency of natural resources, green technologies, and innovation can play a crucial role in low-carbon energy transition and economic development (Ibrahim et al., 2022). Using large-scale data, Song et al. (2019) investigate technological challenges related to green innovation and sustainable resource management. They argue that sustainable utilization of natural resources is becoming crucial due to rising environmental pollution and limitations. Green technological innovation might be one factor leading to the sustainable utilization of natural resources. Countries leading in sustainable economic growth have relied on technological innovation, focusing on efficiently utilizing natural resources and environmental protection activities. Technological innovation can be seen from two main approaches: production-saving and resource-saving (Akhtaruzzaman et al., 2022). Production saving approach leads to increased, albeit efficient, production development. However, this may have adverse implications for environmental protection due to increased production. Secondly, technological innovation from a resource-saving perspective focuses on reduced energy usage and, thus, reduced emissions, but this approach may not stimulate production (Xu et al., 2020). Considering limited resources, long-term sustainable economic growth can be achieved when resources are allocated to these two approaches in a balanced proportion (Song et al., 2019). Fig. 3 shows China's total number of green innovation applications during the last 20 years.

To develop and use key innovations in green and environmental technologies, education and training of the masses and labor force is a must (Umar et al., 2022). Education helps develop high-quality human capital, which is essential to green innovation planning and execution and necessary for economic development (Perez-Alvarez and Strulik, 2021). Interestingly, it is debatable how education and human capital development might affect natural resource usage. On the one hand, a skilled and educated labor force might engage in extensive businesses to earn profits and raise social status. On the other hand, they might go for innovative startups and ventures, significantly reducing dependence on natural resource extraction. Hence, the impact of education on natural resources or economic development is likely to be determined by the tendency of the labor force for green innovations. Fig. 4 shows the number of regular students enrolled in higher education, representing the development of human capital in China during the last 20 years.

The current global economy is facing (1) macroeconomic challenges such as demand shock, supply chain issues, energy poverty (Yan et al., 2023), and inflation problems, (2) challenges to financial markets stability (Iqbal et al., 2022c), and (3) the geopolitical crisis caused by the Russia-Ukraine conflict (Wang et al., 2022a) that has implications for energy commodity prices and supplies. Similarly, the COVID-19 pandemic affecting the Chinese economy has further pressured global economic development. Among these multi-faceted problems, finding solutions to resource constraints requires urgency by policymakers and researchers. Education and green innovation offer various solutions for efficient natural resource management and sustainable development (Rimos et al., 2014). For example, sustainable natural resource management through an educated labor force can improve resource utilization, solving the problem of natural resource constraints faced by global economic development (Prior et al., 2012).

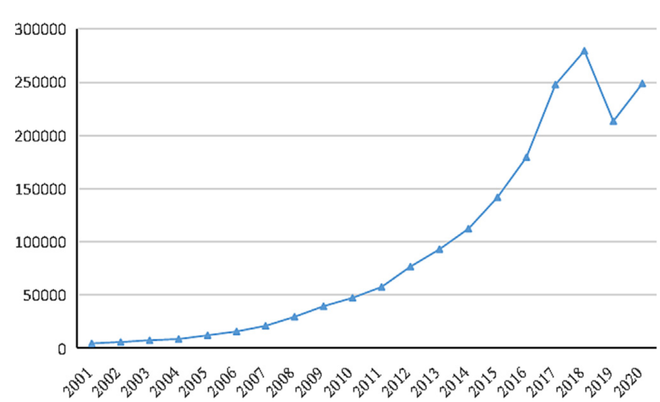

Fig. 3. Number of patent applications for green inventions and green utility models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

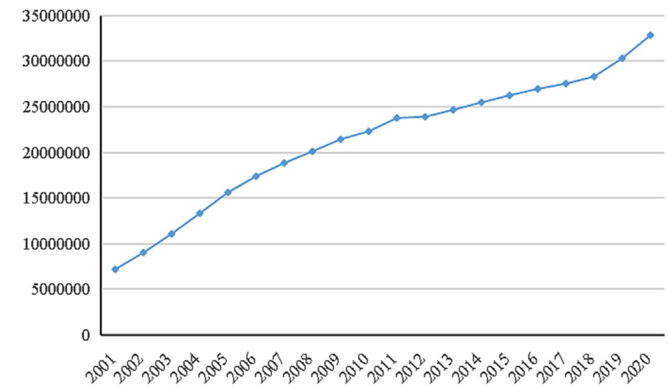

Fig. 4. Number of regular students for standard and short-cycle courses in higher education.

Given the rise in the adverse effect of unsustainable economic development practices (Song et al., 2019), it is becoming a severe issue for policymakers and researchers to comprehend the true dynamics of the multifaceted relationship between sustainable economic development and natural resource mining. In this quest, this study utilizes the provincial data from China during 2001–2020 and examines the impact of natural resource mining on sustainable development. Moreover, this paper discusses how education and green innovation affect the relationship between natural resource mining and economic development.

Our results document four main findings. First, in line with the literature (Chen et al., 2022), natural resource mining negatively impacts sustainable development, referred to as the "curse effect" of natural resources. Second, education and green innovation restrain the negative relationship between natural resource mining and sustainable development, turning the curse effect into blessings. Third, our results report regional heterogeneity in the impact of natural resource mining on sustainable development, which is comparatively more significant in the western and low-urbanized regions. Lastly, green innovation alleviates the curse effect of natural resources in west and low-urbanized areas and reverses the former to the gospel effect.

Policymakers should discourage over-reliance on natural resources and encourage high-value-added industries developed through green innovation and channels. Results suggest regional heterogeneity in the impact of natural resource mining on sustainable development. So, local governments should promote the cross-regional flow of talent, technological knowledge, and capital to provide all regions with fair chances of green development. Our results suggest upgrading green innovation technology that might improve the productivity of existing resources or develop less energy-intensive modes of production, which can be supported by human capital development through education and training. The rest of the paper is structured as follows. Section 2 presents the literature review, and Section 3 offers the research design of our study. Finally, Section 4 provides empirical estimations, and Section 5 presents implications and concluding remarks.

2. Literature review

Rosser (1999) documents that natural resource abundance is associated with adverse development outcomes, and this relationship is mediated by various economic and political factors (such as irrational behavior by political actors). Literature has explored the impact of green innovation on the relationship between natural resources and sustainable economic development (Shah et al., 2022). For example, Chen et al. (2022) analyze the link between natural resources, financial development, green innovation, and environmental sustainability. They find that natural resource rent, financial development, and GDP positively influence carbon emission at higher and lower emissions quantiles. Additionally, green technology innovation greatly mitigates emissions across all quantiles. Below, we document the key studies and findings in the literature on linkages between natural resources, economic development, education, and green innovation.

2.1. Natural resources and economic development

Humans have always aspired to economic development, whereas sustainable economic development should be our common goal, considering the environmental impact (Fleming et al., 2017). Unfortunately, our pursuit of development in the recent past has adversely impacted our environment. Especially since the Industrial Revolution, the quest for economic development became shareholders' profit-maximizing preferences. In this pursuit, natural resources have been exploited and misused, leading us to face issues such as resource constraints and ecological degradation, limiting sustainable development (Keupp and Gassmann, 2013).

Literature has extensively documented factors affecting economic development, e.g., the overall relationship between natural resource extraction and sustainable economic development (see, for example, Rosser, 1999) as well as the environmental impact of unsustainable economic development (Chen et al., 2022). Largely, the literature suggests that traditional methods of natural resource mining cause adverse effects on economic development and the environment (Fei et al., 2016; Chen et al., 2022). Specifically, Zhang et al. (2017) discuss the mutual substitution between environmental protection and economic growth to solve environmental pollution and high energy consumption challenges. Moreover, Grossman and Krueger (1992) document the environmental Kuznets curve (EKC) - an inverted U-curve relationship between pollution levels and per capita income. The EKC implies a potential positive relationship between environmental protection and economic growth after achieving a certain level of economic development (Wang et al., 2016). This relationship can be attributed to green innovation focusing on energy conservation and clean production. Any new and innovative practice or technique can be characterized as green innovation if it achieves resource conservation and environmental improvement. Green innovation is a series of creative activities based on sustainable development preferences that help achieve UNSDGs (Fei et al., 2016; Kunapatarawong and Martínez-Ros, 2016).

2.2. Natural resources, green innovation, and economic development

Green innovation is a possible way to address the challenges of poor environmental quality, excessive energy consumption, and more significant emissions of CO2 (Lin and Ma, 2022). GI is the development of new processes, technologies, services, and production techniques that can significantly reduce pollutant emissions, increase energy efficiency, and exert a net positive effect on the environment (Karimi Takalo et al., 2021). GI is the emergence and maintenance of useful techniques that help reduce environmental costs, develop environmental technologies, and achieve carbon neutrality (Iqbal et al., 2021). It helps develop novel approaches that support the ecological system, prevent it from degradation, and develop a sustainable economic framework (Fengju et al., 2020). GI guides a firm to achieve a good reputation among its stakeholders and increase its financial performance (Peng et al., 2021). Developing and using green technologies can monitor, control, and reduce pollution at the source level. Moreover, it can ensure that the final product production, application, and consumption process have the least negative environmental impact (Patel et al., 2023). Thus, green innovation can be used to eliminate environmental pollution and destruction from the sources of production as well as the final products. Albort-Morant et al. (2016) discuss that green technology innovation can help reduce pollution, save energy, and achieve ecological improvement. Traditional practices and non-green technologies can hardly accomplish these factors that lead to green development. Therefore, policymakers should encourage the adoption of green innovation technology (Umar et al., 2023).

2.3. Natural resources, green innovation, education, and economic development

To achieve environmental sustainability, the role of human capital and green innovation has been debated in limited studies. Past studies have shown that HC has played a significant role in economic development in terms of the efficient utilization of labor (Perez-Alvarez and Strulik, 2021). In addition, HC increases labor productivity if they are educated and have sound knowledge of using technology effectively. Human capital accumulation poses a heterogeneous but positive effect on Green Total Factor Productivity (GTFP) efficiency in the regional context of China (Wang et al., 2021). It is also investigated that HC contributes significantly to energy consumption, especially increasing renewable energy consumption due to education and information access (Zhongwei and Liu, 2022).

Besides this, countries worldwide are paying attention to investing in human capital because of its immense contribution to green growth. For instance, OECD countries are investing in gathering the best human resources worldwide and are the wealthiest countries globally (Yao et al., 2019). Rural human capital is necessary for sustainable rural development and economic growth (Wang and Liu, 2016). The level of HC is crucial for the modernization and development of the industrial structure. When there are more highly qualified and skilled people in the region, it will promote the conglomeration of high-tech industries. The industries with more quantity of labor can attract more investment opportunities in the labor-intensive local manufacturing industries and stimulate growth (Suslova and Volchkova, 2012).

Additionally, due to the higher quality of education attained by the HC, people become aware of risk analysis, and their capacity for risk-taking also increases (Wang et al., 2022b). As green growth and innovation are uncertain (Jin et al., 2019), HC can influence the nexus between natural resources, green innovation, and economic development. Galbreath (2019) has comprehensively highlighted the influence of HC on GI, drawing on the Absorptive Capacity Theory (ACT). The author illustrates that if the board members are highly educated and dexterous, they can easily comprehend complex problems and situations and have reasonable control and monitoring over the firms' operations. Moreover, absorptive capacity can help a firm attract external opportunities and transform them in tangible outputs. Therefore, education positively impacts green innovation and improves environmental performance, leading to sustained competitive advantage (Allameh, 2018). Other than skills enhancement, education leads to high-quality information resources that prompt management to invest more in green projects and innovation. It is interesting to note that natural resources, education, green innovation, and sustainable economic development form a formidable part of the United Nations SDG4, SDG8, SDG9, and SDG12. Specifically, these goals call for quality education, decent economic growth, innovation in infrastructures, and sustainable resource consumption. All of these variables are intermingled to form an essential engine for sustainable economic development.

Given unprecedented Chinese progress and the role of natural resource mining in shaping China as a global economic giant, it is of utmost significance to analyze how different regions practice natural resource mining and its impact on overall development. Using Chinese regional data, we aim to answer the following empirical research questions:

1) What is the role of natural resource mining on overall Chinese economic development?
2) How do green innovation technology and education impact the relationship between natural resource mining and economic development?
3) How does this dynamic interrelation between resource mining, green technology, education, and development vary within different regions of China?

The following section presents data sources and the research methodology to answer the above research questions.

3. Research design

3.1. Samples and data

Considering the data availability and the consistency of statistical caliber, this paper selects 30 provinces, municipalities, and autonomous regions in China from 2001 to 2020 as research samples (Data on the Tibet region is missing, so it is excluded).

The data comes from the National Bureau of Statistics, China Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook on Science and Technology, CSMAR (China Security Market and Accounting Research) database, CNRDS (Chinese Research Data Services Platform) database and Provincial Statistical Yearbooks. As for samples with missing data, the conversion ratio of standard coal is first adopted (1 ton of raw coal is equivalent to 0.714 t standard coal, 1 ton of crude oil is equivalent to 1.43 t standard coal, and 1000 m^3 natural gas is equivalent to 1.33 t standard coal). If the core energy index is missing, the linear interpolation method is used for calculation by referring to Dmitri and Sudipta (2019). All data are Winsorized at 1% to eliminate the interference of outliers or extreme values.

3.2. Variable description

3.2.1. Natural resource mining

Natural resources, especially rich mineral resources, are the foundation of China's industrialization, which is important in industrial development and economic growth. There are many indicators to measure natural resources mining (*Natu*), including the proportion of investment in the mining industry, the ratio of fixed asset investment in the mining industry to that in the whole society, and the ratio of energy industrial output value to the total industrial output value. Considering the significant differences in natural resources among regions in China, the per capita natural resources are finally selected to reflect the regional natural resources and availability for mining. The raw coal, crude oil, and natural gas are included and converted into 10,000 tons of standard coal, by referring to Alexeev and Conrad (2009). Policy factors do not affect this indicator, which can effectively avoid the deviation caused by the different statistical standards and resource abundance in other regions.

3.2.2. Sustainable development

In recent years, sustainable development (*Econ*) has received extensive attention (Cairns and Martinet, 2014; Can and Alatas, 2017; D'Adamo et al., 2022; Tang, 2022). It refers to economic development that does not damage the environment and society, which can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Referring to the studies of Chen et al. (2014) and Ahmed et al. (2022), the GDP growth rate is used to measure sustainable economic development.

3.2.3. Green innovation

Green innovation is an important driving factor for high-quality economic development, considering resource and environmental constraints (Song et al., 2019; Shin et al., 2022). According to the classification of environment-friendly patented technologies by the International Patent Commission (IPC), the number of green patents is used to measure green innovation, according to Liu and Li (2022) and Luo et al. (2022). After adding "1" to each value, the natural logarithm is taken to deal with the right-skewed data distribution.

3.2.4. Education

With the continuous improvement of advanced knowledge, economic growth has shifted from natural physical labor to technological progress and knowledge accumulation. The level of education becomes the primary condition for economic development, which is measured by years of education per capita, by referring to Gregorio and Lee (2002), Kinh and Westbrook (2012), and Wang et al. (2015).

3.2.5. Control variables

According to the neoclassical economic growth theory, physical capital (*Fin*) and human capital (*Hum*) are important driving factors in economic growth. So, they are controlled in this paper, measured by the ratio of fixed asset investment to GDP and the number of students in ordinary colleges and universities, respectively. The following control variables are also controlled, including population density (*Dens*), measured by the ratio of year-end population to the land area; government expenditure (*Gov*), measured by per capita fiscal expenditure; openness (*Open*), measured by the ratio of imports and exports to GDP; industrial structure (*Stru*), measured by the ratio of the secondary industry to GDP; area (*Area*), measured by the land area of the administrative region.

3.3. Model construction

The following basic model Eq. (1) is constructed to test the impact of natural resource mining on sustainable development.

$$Econ_{it} = \alpha + \beta_1 Natu_{it} + \beta_n Controls_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

Where *Natu* is natural resources mining, *Econ* is sustainable development, *Controls* are control variable at the regional level, μ_i is the time fixed effect, α is a constant term; β is the parameter to be estimated; ε is the random interference term.

To explore the role of green innovation and education on the linkages between natural resource mining and sustainable development, their interaction with natural resource mining is introduced in Eq. (2) and Eq. (3).

$$Econ_{it} = \alpha + \beta_1 Natu_{it} + \beta_2 GI_{it} + \beta_3 Natu_{it} * GI_{it} + \beta_n Controls_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

$$Econ_{it} = \alpha + \beta_1 Natu_{it} + \beta_2 Edu_{it} + \beta_3 Natu_{it} * Edu_{it} + \beta_n Controls_{it} + \mu_i + \varepsilon_{it} \quad (3)$$

Where GI_{it} is green innovation, *Edu* is education, $Natu_{it} * GI_{it}$ and $Natu_{it} * Edu_{it}$ are the interaction terms. The coefficient reflects the regulatory effect of green innovation or education in the relationship between natural resource mining and sustainable economic development. Given the nature of our data, we use panel fixed effects modeling, followed by robustness checks through moving averages, adding lagged terms, and changing sample size. Finally, we use the 2SLS approach to counter the threat of endogeneity (Fareed et al., 2022), perform regional heterogeneity, and perform other analyses like urbanization and economic basis levels. The definitions of other variables are the same as provided above.

4. Empirical outcomes

4.1. Descriptive statistics and correlation analysis

The descriptive statistical results of core variables are given in Table 1. The maximum value of sustainable economic development is 0.286, but the GDP growth rate is negative in some years. The maximum and minimum values of natural resources mining are 0.032 and 23.049, respectively, indicating that each region's per capita natural resource production is highly uneven, with a standard deviation of 4.600. The mean of green innovation is 6.598, and the maximum and minimum values are 2.303 and 10.361, respectively. So, green innovation in different regions shows uneven spatial development trend characteristics. Additionally, the average education is 8.655.

The correlation analysis results are given in Table 2, showing a specific correlation between the core explanatory variables and the explained variables. The maximum correlation coefficient between other variables is 0.788, so the selected variables have no serious multicollinearity.

4.2. Panel unit-root test

The unit-root test is required before the panel data regression to avoid incorrect regression. Therefore, the commonly used LLC (Levin et al., 2002), ADF (Dickey and Fuller, 1981), and IPS test (Im et al., 2003) methods are used in this paper, and the results are shown in Table 3. Although some of the original data cannot reject the null hypothesis that there is a unit root, the statistics of the first-order difference term are significant at 1%, indicating that they are stationary sequences.

4.3. Basic regression analysis

This paper first studies the relationship between natural resource mining and sustainable development, and the results are shown in Model (1), Table 4. It can be seen that the coefficient of natural resources mining is −0.002, which is significant at 1%, verifying the resource curse effect (Auty, 2007; Papyrakis and Gerlagh, 2007). On the one hand, in regions with abundant natural resources, the advantage of resource endowment encourages governments to pay more attention to developing the primary industry sectors. It brings crowding out effects on the endogenous drivers of economic growth (Gylfason and Zoega, 2006). It even leads to rent-seeking behaviors, forming an economic structure dominated by natural resource mining. The overall economic efficiency of the region is at a low level. Investments in environmental and social infrastructures are required to mitigate the negative impact of excessive natural resource usage (Umar et al., 2020).

On the other hand, rich natural resources can bring a lot of material wealth in the short term. Due to the weak resource constraint, the regions are not motivated to improve their resource allocation and production efficiency. Meanwhile, the mining and exporting of natural resources further bring about problems such as the reduction of labor participation rate, the single industrial structure, and the destruction of the ecological environment. It results in the dislocation between regional resource endowment and economic growth. Therefore, natural resource mining is insufficient for sustainable economic development.

To further test the mechanism of green innovation and education, this indicator and its interaction term with natural resources mining are introduced into the model, and the results are shown in Model (2) and Model (3), Table 4. It can be found that the coefficient of the interaction terms are −0.001 and −0.004, both of which are significant at 1%, indicating that they can affect the relationship between natural resource mining and sustainable development. It weakens the curse effect of natural resources. Meanwhile, the coefficient of natural resource mining changes from negative to insignificant. It shows that education and green innovation can relieve the curse effect and even reverse it into the gospel effect, which is the key to the high-quality development of China's economy. Our results align with (Kirikkaleli et al., 2023), who report the affirmative role of inventions in environmental technologies on the ecological footprint in the USA, using Fourier ARDL. Education is necessary to implement most of the sustainability-related frameworks about natural resources, such as reducing water extraction (Malmir et al., 2021). Therefore, on the premise that green innovation and education cannot be followed up, effective economic growth cannot be realized only by relying on natural resources mining. More attention should be paid to improving the utilization efficiency of natural resources through technological progress to provide long-term empowerment for sustainable economic development.

Table 1
Descriptive statistics.

Variable	Obs	Mean	Std.Dev.	Min	Max
Econ	600	0.128	0.071	−0.082	0.286
Natu	600	2.942	4.600	0.032	23.049
GI	600	6.598	1.912	2.303	10.361
Edu	600	8.655	1.057	6.040	12.782
Fin	600	0.644	0.255	0.238	1.309
Hum	600	13.155	0.918	10.287	14.556
Dens	600	5.431	1.268	2.030	8.252
Gov	600	8.588	0.987	6.557	10.380
Open	600	0.300	0.363	0.031	1.586
Stru	600	45.129	0.363	0.031	1.586
Area	600	28.002	34.851	0.630	166

Notes: *Econ* shows economic growth rate, *Natu* is natural resources mining, *GI* is green innovation (including green invention and green utility model patents), *Edu* is students enrolled in higher education, *Fin* is physical capital, and *Hum* is human capital, *Dens* is population density, *Gov* is government expenditure, *Open* represents openness as import plus exports divided by GDP, *Stru* is secondary industry to GDP, and *Area* is the land area of the administrative regions.

Table 2
Correlation analysis.

Variable	*Econ*	*Natu*	*GI*	*Edu*	*Fin*	*Hum*	*Dens*	*Gov*	*Open*	*Stru*	*Area*
Econ	1										
Natu	−0.076*	1									
GI	−0.381***	−0.091**	1								
Edu	−0.321***	0.076*	0.686**	1							
Fin	−0.278***	0.239***	-0.007	0.212***	1						
Hum	−0.181***	−0.142***	0.362***	0.756***	0.094*	1					
Dens	−0.029	−0.447***	0.451***	0.527***	−0.344***	0.528***	1				
Gov	−0.410***	0.229***	0.680***	0.665***	0.548***	0.238***	0.029	1			
Open	0.071*	−0.284***	0.510***	0.371***	−0.462***	0.151***	0.480***	0.164***	1		
Stru	0.341***	0.209***	−0.329***	−0.117***	0.043	0.134***	−0.091**	−0.275***	−0.119***	1	
Area	−0.009	0.428***	−0.186***	−0.277***	0.165***	−0.264***	−0.788***	0.044	0.300***	0.051	1

Note: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. For abbreviations, please refer to notes to Table 1.

Table 3
Unit-root test for key variables.

Variable	LLC Statistical value	P value	ADF Statistical value	P value	IPS Statistical value	P value
Econ	−25.856	0.000	84.889	0.000	−15.231	0.000
Natu	−13.838	0.000	23.178	0.000	−9.801	0.000
GI	−18.787	0.000	39.930	0.000	−11.769	0.000
Edu	−28.464	0.000	61.562	0.000	−13.794	0.000

Note: The unit-root test results of core variables are listed. Fore abbreviations, please refer to notes to Table 1.

Table 4
Natural resources and economic development.

Variable	Model (1)	Model (2)	Model (3)
Natu	−0.002***(0.001)	0.006***(0.002)	0.033***(0.007)
GI		0.002(0.005)	
Natu∗GI		−0.001***(0.000)	
Edu		0.019(0.025)	−0.006(0.004)
Natu∗Edu		0.002(0.007)	−0.004***(0.001)
Fin	0.013(0.024)	0.005(0.008)	0.007(0.013)
Hum	0.001(0.007)	0.032**(0.013)	0.005(0.004)
Dens	0.005(0.009)	−0.037*(0.020)	0.011**(0.005)
Gov	0.038***(0.014)	0.001(0.000)	0.000(0.000)
Open	−0.042**(0.021)	−0.000(0.000)	0.040***(0.011)
Stru	0.001**(0.000)	−0.188(0.120)	−0.036***(0.011)
Area	0.000(0.000)	600	0.000(0.000)
Cons	−0.218*(0.126)	0.677	−0.255***(0.092)
N	600	600	600
R^2	0.668	0.690	0.690

Note: Robust standard errors are adjusted for clustering at the regional level in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. For abbreviations, please refer to notes to Table 1.

4.4. Robustness test

4.4.1. Moving average method

The data on green innovation and sustainable development fluctuates wildly yearly, which may lead to deviations in the research results. The moving average method is carried out to eliminate the interference of outliers, and the results are shown in Model (1)-Model (3), Table 5. It can be found that the coefficient of natural resources mining is −0.003, which is significant at 5%. Its interaction terms with green innovation and education are −0.001 and −0.005, respectively, which are significant at 1%. After considering the influence of green innovation and education, the coefficient of natural resources mining changes from negative to positive, which is significant at 1%. It indicates that improving education and green innovation weakens the curse effect of natural resources and changes it to the gospel effect. The above research results are robust.

4.4.2. Changing the sample size

Since Beijing, Tianjin, Shanghai, and Chongqing are municipalities of the central government, they have good political and location advantages. The infrastructure and supporting facilities are relatively complete compared to other regions, which may lead to sample selection bias. So, they are excluded in the robustness test to alleviate the endogeneity problems that may be caused, and the results are shown in Model (4)-Model (6), Table 5. Although the significance of natural resource mining decreases from 1% to 10%, its negative effect on sustainable development still exists. Green innovation and education play a negative regulatory role in this relationship with coefficients of −0.001 and −0.003, which are significant at 1%. Therefore, green innovation weakens the curse effect of natural resources, consistent with the previous conclusions.

4.4.3. Adding the lagged term

Considering the continuity of macroeconomic changes, the lagged term of sustainable development is added to the model for the robustness test. The results are shown in Model (7) - Model (9), Table 5. The lagged term of sustainable development is significantly positive at 1%, indicating that economic growth has a certain path dependence. The coefficient of natural resources mining is still negative, and the significance level decreases to 10%, which verifies its curse effect. The coefficients of the interaction terms are significantly negative, showing that green innovation and education negatively influence the mining and sustainable development of natural resources. Improving green innovation and education reverses the curse effect into the gospel effect. So the above conclusions are still valid after considering the lag of sustainable development.

4.4.4. Considering the endogeneity

Although many control variables are included in this paper, the deviation of research results caused by missing variables should be considered. The explained variable is lagged in two periods to meet the exogenous requirements, according to Wintoki et al. (2012). The 2SLS model is selected for re-estimation, and the results are shown in Model (10)-Model (12), Table 5. It can be found that

Table 5
Robustness and Endogeneity tests.

Variable	Moving average method			Changing the sample size		
	Model (1)	**Model (2)**	**Model (3)**	**Model (4)**	**Model (5)**	**Model (6)**
Natu	−0.003**	0.008***	0.041***	−0.002*	0.004*	0.028***
	(0.001)	(0.002)	(0.006)	(0.001)	(0.002)	(0.007)
GI		0.003			−0.000	
		(0.003)			(0.003)	
*Natu*GI*		−0.001***			−0.001***	
		(0.000)			(0.002)	
Edu			−0.002			−0.008
			(0.004)			(0.005)
*Natu*Edu*			−0.005***			−0.003***
			(0.001)			(0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Cons	−0.307*	−0.257***	−0.359***	−0.365**	−0.335***	−0.360***
	(0.169)	(0.082)	(0.080)	(0.186)	(0.127)	(0.120)
N	600	600	600	520	520	520
R^2	0.621	0.659	0.670	0.699	0.706	0.721
Variable	**Adding the lagged term**			**Considering the Endogeneity**		
	Model(7)	**Model(8)**	**Model(9)**	**Model(10)**	**Model(11)**	**Model(12)**
L.Econ	0.326***	0.311***	0.286***			
	(0.043)	(0.038)	(0.038)			
Natu	−0.001*	0.003*	0.022***	−0.001*	0.006**	0.053***
	(0.000)	(0.002)	(0.006)	(0.001)	(0.003)	(0.009)
GI		0.002			−0.001***	
		(0.003)			(0.000)	
*Natu*GI*		−0.001**			−0.013***	
		(0.000)			(0.004)	
Edu			−0.005			−0.001
			(0.004)			(0.005)
*Natu*Edu*			−0.002***			−0.006***
			(0.001)			(0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Cons	−0.031	−0.009	−0.103	0.554***	0.256***	0.435***
	(0.070)	(0.087)	(0.083)	(0.049)	(0.084)	(0.051)
N	570	570	570	540	540	540
R^2	0.748	0.750	0.759	0.861	0.868	0.871
Sargan				74.751***	57.796***	55.741***

Note: Robust standard errors are adjusted for clustering at the regional level in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. For abbreviations, please refer to note to Table 1.

the regression results of core variables have not changed significantly. Natural resource mining hurts sustainable development, which is weakened after considering the role of green innovation and education. Therefore, the above research results are robust.

4.5. Further analysis

4.5.1. Difference in the economic basis

China's economy is characterized by unbalanced development. The eastern regions, such as Beijing, Jiangsu, Guangdong, and Zhejiang, have abundant capital, complete infrastructure, and relevant supporting measures. While the Western regions such as Gansu, Xinjiang, and Qinghai have weak economic foundations, which will affect the economic effects of natural resources. So, all regions in China are divided into the eastern, central, and western areas according to the classification standard proposed by the National Development and Reform Commission, as shown in Table 6.

The regional heterogeneity test is conducted by grouping regression, and the results are shown in Table 7. We see a negative but insignificant impact of natural resource mining on sustainable development in the eastern and central regions, indicating an ambiguous curse effect. However, it is significant at 5% in the western regions, showing that natural resource mining significantly inhibits the increase of economic growth. The reason may be that the eastern and central areas have a weak natural resource base, and they have to put production factors into innovation activities to eliminate resource constraints. The traditional economic development mode relying on natural resources can be changed through innovation and technological progress.

The western regions have the resource endowment advantage, making it give priority to the development of traditional resource-based industries. It has a squeezing effect on other economic activities. Due to excessive dependence on natural resources, low-end technology is locked in. The low marketization makes it more difficult to play the spillover effect of other regions' knowledge, capital, and technology. The lack of a market price and interest coordination mechanism further intensifies the blind development of natural resources in the Western regions. Ultimately, it hinders the vertical extension of resource-based industries to higher value-added industrial chains. With the implementation of energy projects such as west-to-east energy transmission, the loss of production factors and the trade fluctuation effect are caused. The western regions have to bear the resulting environmental pollution, which negatively impacts sustainable development. Additionally, the coefficient of natural resources mining in the western regions changes from negative to positive

Table 6
Regional division.

Category	Regions included
Eastern regions	Beijing, Tianjin, Hubei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, Hainan
Central regions	Jilin, Heilongjiang, Inner Mongolia, Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan
Western regions	Chongqing, Sichuan, Guizhou, Yunnan, Shanxi, Gansu, Qinghai, Ningxia, Xinjiang

Note: Table 6 shows which provinces and autonomous regions are divided into eastern, western and central regions.

Table 7
Regional heterogeneity caused by the economic basis.

Variable	Eastern regions	Central regions	Western regions		
	Model (1)	**Model** (2)	**Model** (3)	**Model (4)**	**Model (5)**
Natu	−0.011	−0.003	−0.001**	0.005*	0.039**
	(0.007)	(0.002)	(0.001)	(0.003)	(0.016)
GI				0.002	
				(0.004)	
Natu∗*GI*				−0.001**	
				(0.000)	
Edu					0.013
					(0.009)
Natu∗*Edu*					−0.0004***
					(0.002)
Controls	Yes	Yes	Yes	Yes	Yes
Cons	−0.202	−0.704*	−0.321**	−0.433**	−0.284
	(0.167)	(0.784)	(0.144)	(0.196)	(0.239)
N	240	180	180	180	180
R^2	0.697	0.706	0.746	0.749	0.758

Note: Robust standard errors are adjusted for clustering at the regional level in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01. For abbreviations, please refer to notes to Table 1.

after considering the role of green innovation and education. It shows that green innovation and education are the key variables to breaking the curse effect of natural resources in the western regions. Hence, our analysis points towards the positive role of GI and education in inhibiting the negative consequences of excessive natural resource mining in the western regions of China. The local governments in this region need to emphasize technical education and skill enhancement to produce a high-quality labor force that can support the process of green transition and innovation.

4.5.2. Differences in urbanization levels

The urbanization level of different regions in China is quite different. For example, in 2021, the urbanization rate of Shanghai and Beijing reached 89.31% and 87.48%, respectively, while that of Yunnan was only 51.04% (Fig. 5). With the geographical agglomeration of production factors, information exchange, and resource flow are accelerated, which promotes the labor division, transactional efficiency, and industrial cluster development (Zhou et al., 2023). Urbanization plays the positive externality of the agglomeration effect and then indirectly acts on regional economic growth. Urbanization is found to be one of the most critical factors affecting ecological balance and sustainability in the cities of the global south (Das et al., 2023a). Rapid and unplanned urbanization has led to excessive ecological risks in the past twenty years (Das et al., 2023b). So, it's important to account for this very critical factor.

Therefore, the curse effect's intensity may differ in regions with high and low urbanization levels. This paper takes the average urbanization level of China each year as the standard and divides samples into two groups. The results in Table 8 show that the coefficients of natural resource mining are −0.007 and −0.003, respectively, in those two groups. The former is insignificant, while the latter is significant at 5%, indicating that regions with high urbanization levels are less affected by the curse effect. It is consistent with the conclusions of existing scholars (Stevens, 2006). The main reason may be that urbanization promotes the high concentration of talent and knowledge and broadens the channels of information and technology diffusion, which can obtain higher economic benefits and scale effects (Rice et al., 2006).

In addition, the coefficient of the interaction term between natural resource development and education is −0.003, which is significant at 1%. The influence of education even reverses the curse effect of natural resources to a gospel effect, while it is not significant after considering the role of green innovation. The findings align with Zhao et al. (2023) and Sharma et al. (2021), who emphasize the role of human capital and green innovation for sustainable development in China and the BIMSTEC region. The result means that green innovation can alleviate the curse effect in regions with low urbanization but cannot reverse it to a gospel effect. The reason may be that the spatial agglomeration of various factors, such as talent, public services, and infrastructure, is relatively slow in those regions. The economic benefits of green innovation are hard to achieve in the short term, so it's not enough to reverse the curse of natural resources.

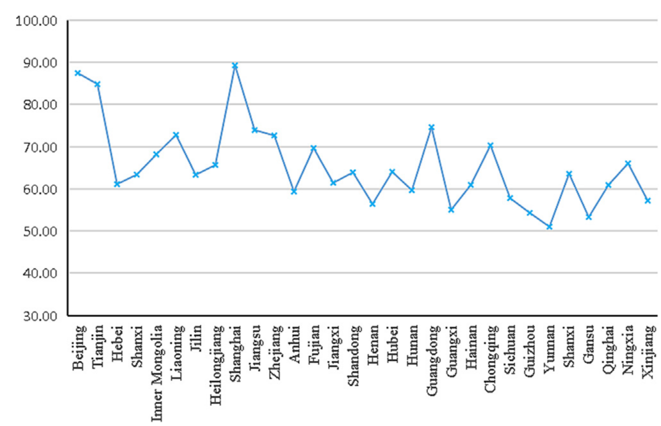

Fig. 5. Urbanization rate in different regions in 2021.

The negative consequences of excessive natural resource mining can be mitigated through promoting education and green innovation (Ma et al., 2023), especially in China's western (resource-rich) region. By working on the United Nations' SDG4 (quality education), and SDG9 (innovation and industrial infrastructure), the Chinese government can achieve SDG8 (decent work and economic growth) and SDG12 (responsible production) easily. Policies should be aligned with the conducive development of the green energy sector by minimizing the uncertainties (Bouri et al., 2022). This path aligns with the key takeaways from the COP27 as well, which stresses mobilizing more resources and pivoting the implementation of green mechanisms. Investments in education and innovation can also be framed in a public–private partnership context to enhance efficiency and improve transparency (Cheng et al., 2021). Table 9 shows the acronyms used in the study.

Table 8
Regional heterogeneity caused by urbanization level.

Variable	High urbanization	Low urbanization		
	Model (1)	**Model** (2)	**Model** (3)	**Model (4)**
Natu	−0.007(0.007)	−0.003**(0.001)	0.003(0.002)	0.028***(0.008)
GI			0.002(0.004)	
Natu∗GI			−0.001***(0.000)	
Edu				−0.003(0.006)
Natu∗Edu				−0.003***(0.001)
Controls	Yes	Yes	Yes	Yes
Cons	−0.493(0.683)	−0.582***(0.189)	−0.496***(0.164)	−0.497***(0.159)
N	140	460	460	460
R^2	0.593	0.702	0.707	0.719

Note: Robust standard errors are adjusted for clustering at the regional level in parentheses; **p* < 0.1, ***p* < 0.05, ****p* < 0.01. For abbreviations, please refer to notes to Table 1.

5. Conclusions and implications

5.1. Conclusions

This paper explores the relationship between natural resource mining, green innovation, and sustainable development. It aims to reference policy optimization and improve the efficiency of natural resource utilization. The framework and results of this paper are shown in Fig. 6.

The main conclusions are as follows: First, natural resource mining hurts sustainable development in China, which verifies the curse effect of natural resources. It shows that only excessive usage of natural resources is insufficient for economic growth. Second, education and green innovation weaken the negative impact of natural resources on sustainable economic growth, which are the keys to breaking the curse effect of natural resources. The reversal of the curse into a gospel effect indicates that green innovation transforms China's economy from factor-driven to innovation-driven. Third, the natural curse effect is mainly concentrated in the western regions and those with low urbanization levels. Education and green innovation minimize the harmful and curse effect into gospel effect more in the western areas but not in the low-urbanization regions.

5.2. Policy implications

First, the Chinese government should avoid seeking resource-consumption-led economic growth due to the Curse Effect. Although the authorities have already built a narrative of high-quality development pursuit, returning to excessive resource mining is plausible in the wake of climate risks. In light of the findings in this study, electricity production from natural resources like Coal (which is put into the picture due to water shortages from heat waves) may harm sustainable economic development. Measures should be taken to upend the resource-based industrial chain and transform it into high-value-added industries to overcome the problems related to the monotonous industrial structure and create new economic growth poles. To improve the added value of natural resources, seeking the horizontal transfer of production factors between industries and introducing advanced exploration and processing technology is necessary.

Table 9
Acronyms.

PPP	Purchasing Power Parity	**UNSDGs**	United Nations Sustainable Development Goals
GI	Green Innovation	**HC**	Human Capital
GTFP	Green Total Factor Productivity	**OECD**	Organization for Economic Cooperation and Development
ACT	Absorptive Capacity Theory	**CSMAR**	China Security Market and Accounting Research database
CNRDS	Chinese Research Data Services Platform	**GDP**	Gross Domestic Product
IPC	International Patent Commission	**2SLS**	Two Stage Least Squares
LLC	Levin-Lin-Chu unit-root test	**ADF**	Augmented Dickey Fuller unit-root test
IPS	Im-Pesaran-Shin unit-root test	**ARDL**	Auto Regressive Distributed Lag
COP	Conference of Parties	**BIMSTEC**	The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation

Second, as green innovation plays an important role in breaking the curse effect of natural resources, government departments should strengthen the element's input and policy support for green innovation. Under their guidance, local governments should promote cross-regional talent, capital, information, and knowledge flow. The low-end technology lock can be broken by giving full play to active innovation areas' positive spatial spillover effects. For natural resource-based industries, efforts should be made to promote the transfer of production factors toward higher value-added industrial sectors and foster capital-intensive and technology-intensive industries, essential sources of sustainable economic growth.

Third, there is regional heterogeneity in the impact of natural resource mining on sustainable economic growth. So, policies should be formulated according to local conditions, significantly improving innovation infrastructure and supporting services in the western regions. They can eliminate the traditional development path of the resource-based industry through innovation. It is also recommended to enhance the agglomeration effect of urbanization and improve the pricing and interest mechanism of natural resources, which can lead to optimal utilization. All of this process can be accelerated through technical skills and technology-based education provision. Due to regional heterogeneity in natural resource production and consumption, connectivity projects like the One Belt One Road should be contextualized in the Western regional development.

5.3. Future research directions

As the current geopolitical situation caused by the Russia-Ukraine conflict may alter the energy landscape and climate change mitigation efforts (Patel et al., 2023), future studies should examine this conflict's short- and long-run effects on sustainable economic growth worldwide. Given the recent climatic experience and teh end of the COVID-19 pandemic, future studies should explore the likely challenges brought by policy uncertainties (Bouri et al., 2022), and pandemics (Naeem et al., 2023), and effec-

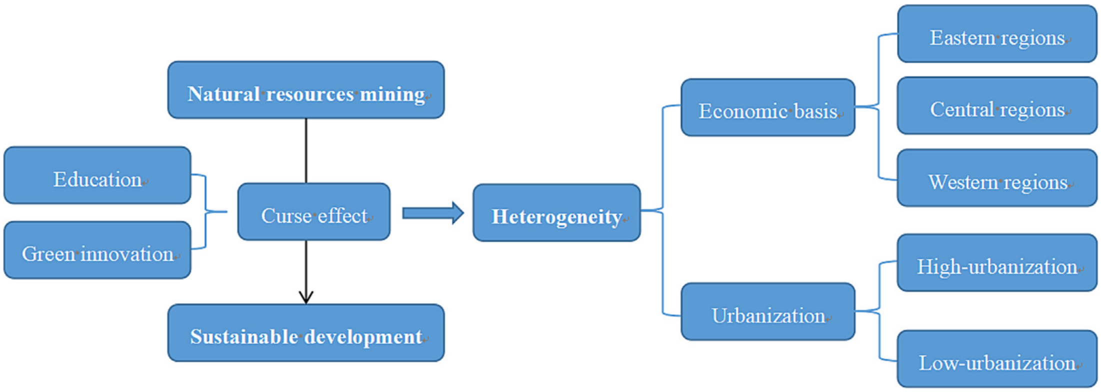

Fig. 6. Framework and results of this paper.

tive strategies to deal with such possible events in the context of sustainable management of natural resources, especially the crude oil.

CRediT authorship contribution statement

Xing Li: Funding acquisition, Writing - original draft, Writing - review & editing. **Lina Ma:** Conceptualization, Methodology, Data curation, Software, Formal analysis, Funding acquisition. **Asif M. Ruman:** Investigation, Visualization, Writing - original draft. **Najaf Iqbal:** Validation, Investigation, Project administration, Resources. **Wadim Strielkowski:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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