Correlation analysis of energy consumption, carbon emissions and economic growth

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Abstract

In today's highly advanced industrialised and modernised world, China's economy is still growing, and its demand for energy is increasing daily. It is crucial to examine the connection between energy consumption, carbon emissions, and economic growth in order to promote economic growth based on energy conservation and emission reduction. Using Dezhou City in Shandong Province as an example, the study builds a VAR model of carbon emission, energy consumption, and economic growth in Dezhou City based on simplified macroeconomic sub-models, energy sub-models, and environmental sub-models. It then determines the correlation and influence mechanism between the three using tests like ADF unit root and Granger causality. The pertinent elements affecting Dezhou's carbon emissions were then investigated using grey correlation analysis. Finally, based on the study's findings, policy suggestions are made regarding energy use, carbon emissions, and economic expansion. It is necessary not only to restrain high-energy consumption industries and fundamentally optimize the energy consumption structure, but also to find new economic growth points and improve economic growth channels, so as to optimize the industrial structure. In this process, increasing the proportion of the tertiary industry is a key measure. In addition, the government needs to advocate the citizens to adopt a low-carbon lifestyle, and the concept of low-carbon environmental protection will be deeply rooted in the hearts of the people. This study will provide suggestions and theoretical guidance for China's energy consumption and carbon emissions, and help achieve high-quality growth of China and even the world economy.

Keywords: Energy, Carbon emissions, Economic growth, Grey correlation analysis, Granger causality, ADF unit root

Introduction

Energy consumption (EC), carbon emissions (CE) and economic growth (EG) are key factors in today's world economic development (Dabboussi and Abid 2022). The analysis of the relationship between these three is of great significance for the formulation of effective energy saving and emission reduction measures and the promotion of sustainable economic development (Rodríguez-Caballero 2022). However, existing studies mostly focus on the separate analysis of EC and EG or CE and EG, and lack a comprehensive discussion on the deep relationship between the three (Li et al. 2021a). In addition, most studies focus on macro-regions, making it difficult to provide targeted guidance

for the economic development of specific cities (Sun et al. 2020). Based on energy-economy-environment (3E) theory and environmental Kuznets (EKC) curve theory, the VAR model including EG, EC and CE was constructed to analyze their correlation. Through the ADF unit root (ADF-UR), Granger causality (GrgC) and grey correlation analysis (GCA), the influence mechanism between the three is discussed. The research results will provide data and theoretical support for local policy making to help balance EC, CE and EG, and ensure environmental protection and sustainable development. Compared with previous studies, this study provides analysis at the specific city level and makes up for the deficiency of local guidance in macro studies (Safi et al. 2021; Salari et al. 2021). The GCA method is used to provide a more detailed analysis of the correlation strength between variables, which provides a more targeted basis for policy making. These innovations will provide new perspectives and theoretical guidance for China's CE regulation and high-quality EG, which will help achieve the sustainable development Goals.

Related works

The use of fossil fuels has increased over time due to the complementary growth of research, technology, and the economy. As a result, the quantity of CE generated by the use of fossil fuels has increased, and environmental degradation has gotten progressively worse. The widespread usage of fossil fuels today has put the sustainable exploitation of natural resources and the growth of numerous enterprises in some danger. In order to create a sustainable supply of resources and maintain the peaceful coexistence of man and nature on the basis of ensuring economic progress, it is vital to study the correlation between EC, CE, and EG. For this reason, many scholars have included EC, CE and EG in the same research system, so as to analyse the correlation between the three. To investigate the short- and long-term causal linkages, Zhang and Zhang employed the GrgC of the vector error correction model (VECM) to examine the pertinent data of 30 Chinese provinces from 2000 to 2017. The findings of the empirical analysis indicate that CE dioxide and GDP, CE dioxide and tourism, and GDP and tourism all have long-term causal interactions that are bidirectional (Zhang and Zhang 2020). Adebayo and Kirikkaleli used wavelet statistical tools to analyse the link between CE dioxide and GDP growth, renewable energy, technological innovation and globalisation using the dataset of Japan, they studied the environmental degradation problem in Japan and proposed appropriate countermeasures to promote the development of the renewable energy market in Japan (Adebayo and Kirikkaleli 2021). To examine the connection between CO_2CE, biomass consumption, EG, and urbanisation, Gao and Zhang performed a survey of 13 developing Asian nations. The outcomes of the empirical research demonstrated that there is a unidirectional causal relationship between CE dioxide, biomass consumption, urbanisation, and GDP, as well as a long-run equilibrium relationship between these four (Gao and Zhang 2020). Li et al. studied the specific situation of different income groups in 147 countries from 1990 to 2015, so as to analyse the impact of per capita CE on the structural changes of the local economy, energy, society and trade, and consequently put forward CE reduction countermeasures (Li et al. 2021b). Gessesse and He used the autoregressive distributed lag (ARDL) limits test of cointegration and error correction model (ECM) to assess CE dioxide, EC, and GDP in China during the previous 30 years in order to determine the correlation between the three. The findings

indicate that, from a long-term viewpoint, there is a considerable negative causal link between CE dioxide and GDP and energy use (Gessesse and He 2020).

To address the issue of environmental pollution brought on by the expansion of renewable EC in India, Jayasinghe and Selvanathan used autoregressive distributional lag and vector error correction modelling frameworks to analyse the correlation between EC, CE, GDP, and international tourism development in India over the last three decades. The study concludes that sustainable tourism, EC and EG should be placed at the top of India's economic development agenda (Jayasinghe and Selvanathan 2021). Wada et al. analysed the effects of traditional EC on environmental quality from the dimensions of EC, import trade, export trade and national EG, using Brazil as an example. Therefore, Brazil, in the process of economic development, needs to carefully comply with conservation policies to promote environmental sustainability, so that the Brazilian economy can develop healthily (Wada et al. 2021). Li and Haneklaus conducted a survey on cleaner EC, GDP, trade openness, urbanisation and CO_2 in the Group of Seven (G7) economies over the last 40 years to explore the potential linkages between them. The empirical analysis verified the existence of an environmental Kuznets curve and showed that trade openness increases CE and urbanisation increases and decreases CE. The study contributes to the promotion of sustainable development in energy production and consumption and environmental quality (Li and Haneklaus 2022). Hasanov et al. proposed a theoretical framework so as to quantitatively analyse the impact of technological progress, renewable EC and international trade on CE. The results of the quantitative analyses showed that technological progress, renewable EC and the scale of exports contribute to the reduction of CE dioxide, while gross domestic product and the scale of imports increase pollution in both the long and short term (Hasanov et al. 2021). To evaluate the association between international tourism, EC, CO_2CE, and EG in these countries, Aslan et al. analysed information on pertinent data for Mediterranean nations for the years 1995 to 2014. A panel quantile regression model was modelled on the relevant data and analysed to obtain the correlation between the different factors, providing a theoretical reference for the sustainable development of tourism in Mediterranean countries (Aslan et al. 2020). Haque analysed the correlation between oil price shocks, EC, CE, and GDP per capita using static panel estimation and dynamic panel estimation methods over a 30-year data period for the GCC countries. The empirical analysis found that population growth is positively correlated with EC, while EC is positively correlated with the amount of CE dioxide. Therefore, measures need to be taken to save energy and reduce emissions and implement demand side management (Haque 2020).

To sum up, when discussing the relationship between EC, CE and EG, existing studies mainly focus on the macro level, usually covering the data of countries or multiple provinces. Although these studies reveal important links between EC and EG, and between CE and EG, their application at the specific city level is limited. Most of the existing studies use vector error correction model (VECM), Granger causality analysis and other methods, but lack in-depth discussion of the actual situation of specific cities, and it is difficult to provide targeted policy recommendations. In contrast, this study takes Dezhou City as an example to comprehensively explore the correlation and influence mechanism among the three by constructing VAR models including EG, EC and CE, and combining ADF unit root test, Granger causality test and grey correlation

degree analysis. This study not only fills in the gaps in specific city-level analysis, but also reveals a more complex dynamic between EC, CE, and EG at the local level. Through detailed analysis of the strength of the correlation between variables, the research results challenge the macro perspective of the relationship between EC, CE and EG in existing theories, and verify the complex correlation between different variables at the micro level. This research results provide a more targeted basis for local policy formulation, help achieve the coordinated development of EC, CE and EG, ensure environmental protection and sustainable development, and thus provide a reference for other cities to promote the theoretical and practical progress of China's carbon emission regulation and high-quality EG.

VAR model construction for EC, CE and EG

Global warming and energy overconsumption have become the key concerns of the current research community, and changing the high CE situation to achieve low-carbon, green, and sustainable economic development has become the primary issue of each country, so it is necessary to analyse the correlation between EC, CE and EG (Raza and Shah 2020; Karimi et al. 2023). To this end, the study takes the historical data of Dezhou city as an example, and constructs a VAR model including EG, EC and CE, so as to analyse the correlation between the three factors.

EG, EC and CE in Dezhou City and data selection

In order to better describe the correlation between Dezhou city EG, EC and CE, the study introduced the energy-economy-environment (3E) theory and the environmental Kuznets (EKC) curve theory (Gardiner and Hajek 2020). Among them, the 3E theory is extended from the sustainable development theory, and is divided into three types according to the differences in the analysis ideas (Barma and Modibbo 2023). The basic types of the 3E theory models are shown in Fig. 1.

Taking into account the practical needs and the difficulty of obtaining relevant data, the study adopts a top-down model to explore the correlation between EC, CE and EG. The EKC curve is a commonly used tool for analysing the correlation between EG and the income gap of the population. As the environmental pollution problem is getting more and more attention, some researchers have borrowed the idea of EKC curve and included environmental pollution into the research framework as well. The EKC curve is shown in Fig. 2.

Combining the EKC curve and the 3E theory, as well as the relevant data of EC, CE and EG in Dezhou city, it is able to analyse the correlation between EC, CE and EG in Dezhou city. Through the relevant documents made public in Dezhou city, the study collected the relevant data of Dezhou city from 1983 to 2019, including Dezhou city statistical yearbook, Dezhou city energy development report, etc., so as to obtain the development of EG, EC, and CE in Dezhou city. The study describes the EG situation of Dezhou city in terms of its total GDP, GDP growth rate, and economic structure characteristics, as shown in Fig. 3. In Fig. 3a, the total GDP and GDP growth rate of Dezhou city from 1983 to 2019 are demonstrated. In Fig. 3b, it is the transformation of the economic industrial structure characteristics of Dezhou city in the last 30 years. As can be seen from Fig. 3a, the total GDP of Dezhou showed a significant growth trend from
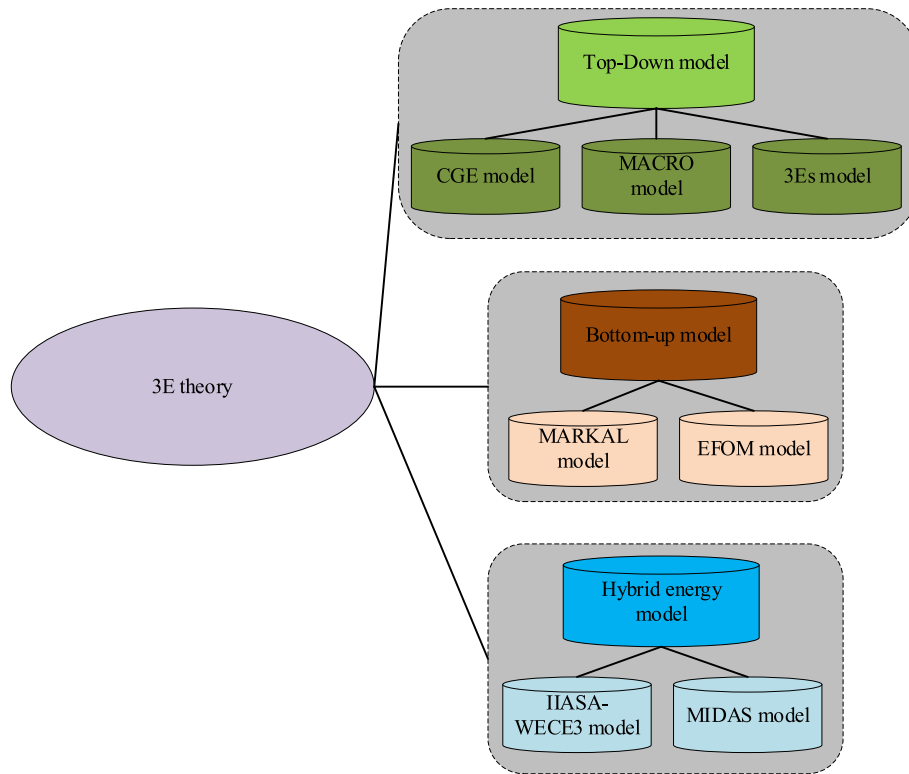
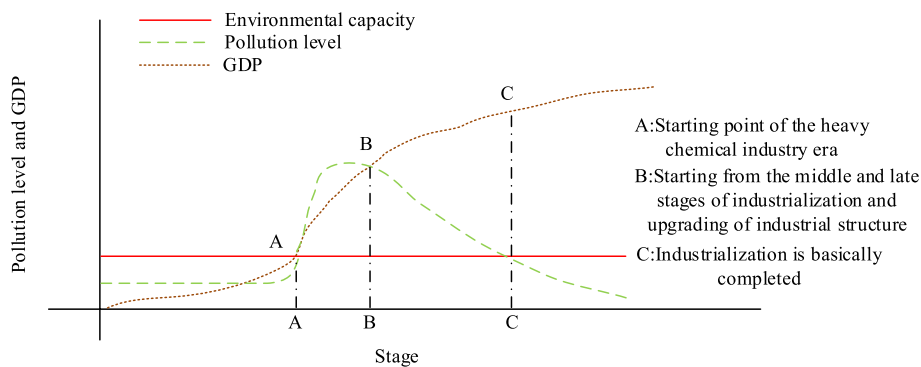**Fig. 1** Basic types of 3E theoretical models

Fig. 2 EKC curve

1983 to 2019, especially after 2000, the GDP growth rate accelerated. Although there are fluctuations in the GDP growth rate, the overall trend is upward, especially after 2000, there is a significant rise. This indicates that the economy of Dezhou City experienced rapid development during this period. As can be seen from Fig. 3b, the proportion of the primary industry in GDP showed a gradual decline from 1983 to 2015. The proportion of the secondary industry in GDP initially declined, but stabilized after 2000. The share of the tertiary sector in GDP has shown a significant upward trend, especially after 2000, when growth accelerated. Figure 3 shows that Dezhou experienced rapid economic growth from 1983 to 2019, with both the total GDP and the growth rate rising
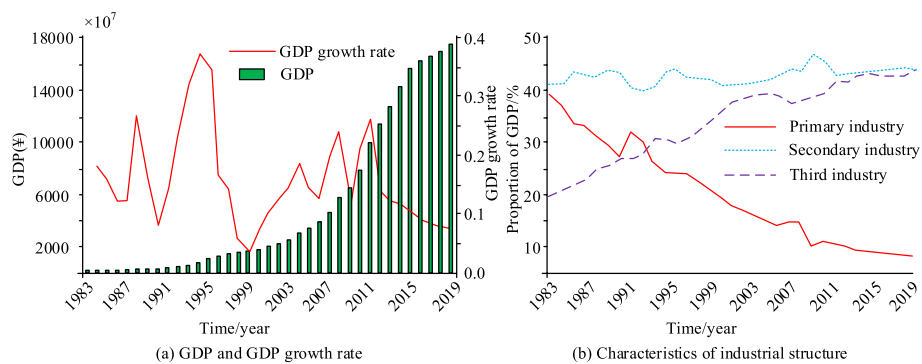
(a) GDP and GDP growth rate

(b) Characteristics of industrial structure

Fig. 3 The total GDP, GDP growth rate, and economic structure characteristics of Dezhou city

(a) The energy consumption structure
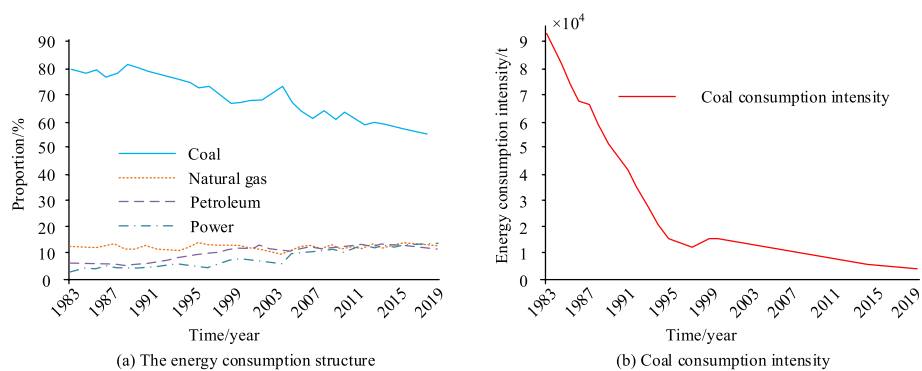
(b) Coal consumption intensity

Fig. 4 The EC structure and intensity of Dezhou city

significantly. At the same time, the industrial structure of the economy has changed significantly, with the proportion of the primary industry declining and the proportion of the tertiary industry increasing. This shift has helped to improve the diversity and stability of the economy, but it may also bring new challenges, such as the need for more efficient energy use and stricter environmental protection measures to support sustained economic development and low-carbon transition.

Figure 4 illustrates how the structure and intensity of energy use are used to analyse Dezhou City's 30-year EC history. The most significant source of EC in Dezhou City is coal, as shown in Fig. 4a. In the development process, the share of coal EC has decreased somewhat, but it is still significantly higher than the EC of natural gas, oil, and electricity. Therefore, the study assesses the intensity of EC in Dezhou city through the consumption of coal, as shown in Fig. 4b. In the process of development, the consumption of coal decreases year by year. It can be illustrated through Fig. 4 that the economic and technological level of Dezhou City is improving, the efficiency of energy utilisation is improving, and the consumption ratio of natural gas, oil and electric energy is increasing. These trends show that while Dezhou is gradually reducing its dependence on coal, coal remains a major source of energy, which leads to high carbon emissions. With the increasing proportion of natural gas, oil and electricity consumption, energy utilization efficiency has been improved, but the energy consumption structure of Dezhou still needs to be further optimized to reduce carbon

emissions and environmental pollution. These trends have an important impact on Dezhou's energy policy and carbon emission control. Dezhou needs to speed up the adjustment of energy structure, promote clean energy and improve energy efficiency to achieve low-carbon economy and sustainable development goals.

With reference to the established literature and the structure of EC in Dezhou city, the study constructed a carbon decomposition model, as shown in Eq. (1).

$$C = \alpha E_c + \beta E_o + \gamma E_g \tag{1}$$

In Eq. (1), α is the carbon emission conversion factor coefficient of coal; β is the carbon emission conversion factor coefficient of petroleum; γ is the carbon emission conversion factor coefficient of natural gas; C is the total carbon emissions, expressed in tons (t); E_c is the total coal consumption, the unit is ton (t); E_o is the total oil consumption, expressed in tons (t); E_g is the total natural gas consumption, the unit is cubic meters (m^3); According to the corresponding document published by the National Development and Reform Commission, the carbon emission conversion factor coefficients of coal, oil and natural gas are 0.746, 0.583 and 0.444, respectively. CE intensity is the value obtained by dividing the total volume of CE by the GDP in a specific region, and it is able to reflect the impact of GDP growth on the increase of CE volume. The trends of CE intensity and total CE volume in Dezhou city over the past 30 years are shown in Fig. 5. It can be seen that the total carbon emission of Dezhou city is increasing year by year, which indicates that the industrialization process of Dezhou city is constantly accelerating. At the same time, carbon intensity has been declining year by year, especially since the mid-1990s. This trend shows that although the total carbon emissions of Dezhou city are increasing, the carbon emissions per unit of economic output are decreasing, reflecting the improvement of the energy consumption structure and industrial efficiency of Dezhou city. The rise in total carbon emissions is consistent with the increase in economic growth and energy consumption in Dezhou city, confirming the conclusions of the study on the importance of energy consumption to economic growth. The decline in carbon emission intensity indicates that Dezhou city has made certain progress in improving energy
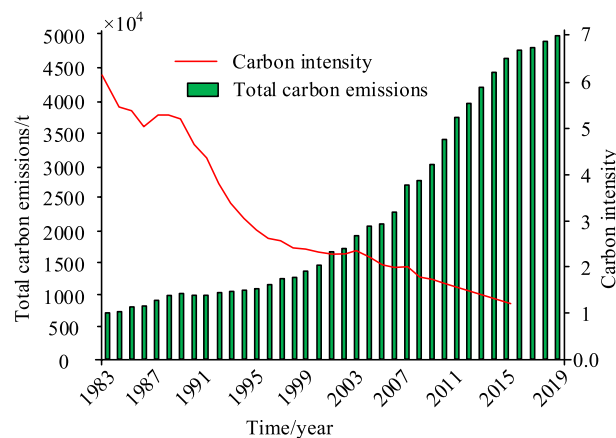

Fig. 5 Changes in carbon emission intensity and total CE

utilization efficiency and optimizing energy structure, especially reducing its dependence on high-carbon energy sources (such as coal). But there is still a need for more targeted policies to control the overall rise in carbon emissions while ensuring sustainable economic development.

Based on the 3E theory, the development status of Dezhou City and previous studies, data selection is made, and GDP is chosen to represent the economic growth of Dezhou City. As a representative indicator of economic growth, GDP is widely used to measure the economic development level of a region. In many studies, GDP has been shown to be an important factor affecting energy consumption and carbon emissions. Energy consumption EN in Dezhou city is selected to represent the energy index. Energy consumption is the main driver of economic activities and also an important source of carbon emissions. Choosing EN as an energy index can directly reflect the energy use of Dezhou city and provide a basis for analyzing its impact on economic growth and environmental quality. Carbon emission CO_2 in Dezhou city is chosen to represent the environmental quality index, and carbon emission is an important index to measure environmental quality. By selecting CO_2 as a representative of environmental quality, the impact of economic growth and energy consumption on the environment can be analyzed, thus providing data support for the formulation of effective emission reduction policies. Finally, the relationship between GDP, EN and CO_2 is analyzed through 3E system. Another key reason for choosing these variables was their consistency and reliability across different studies, which can provide a solid theoretical and data foundation for this study. In addition, in order to avoid large errors between the results obtained by subsequent model construction and the real results, the analysis results have no reference significance, the above indicators are processed in the research, that is, the above indicator variables are transformed by natural logarithm and recorded as $LnGDP, LnEN, LnCO_2$ respectively. However, the selection of these variables also has certain limitations. For example, GDP as an indicator of economic growth, although it has a wide range of applications, but it can not fully reflect a region's economic structure changes and social welfare level. In addition, there may be measurement errors and statistical biases in the data of energy consumption and carbon emissions, which may affect the estimated results of the model. Therefore, these potential biases and limitations need to be fully considered when interpreting the results of the analysis. The ensuing model development and correlation analysis are done in accordance with the data indicator variables displayed in Tables 1 in 2.

Table 1 Data selection situation

Project	Index	Code	Unit
Gross domestic product	EG in Dezhou city	GDP	Billion
EC	Energy indicators	*EN*	10,000 tons of standard coal
CE	Environmental quality indicators	CO_2	t
Natural logarithm transformation of GDP indicators	–	*LnGDP*	–
Natural logarithm transformation of EC	–	*LnEN*	–
Natural logarithm transformation of CE	–	$LnCO_2$	–

Table 2 ADF Root of unity test results

Project	lnGDP	△lnGDP	$\triangle^2$ lnGDP	lnEN	△ lnEN	$\triangle^2$ lnEN	lnCO$_2$	△lnCO$_2$	$\triangle^2$ lnCO$_2$
(C,T,K)	(C,T,0)	(C,T,1)	(C,T,2)	(C,T,0)	(C,T,0)	(C,T,2)	(C,T,1)	(C,T,1)	(C,T,2)
ADF value	− 3.02	− 2.28	− 6.38*	− 0.10	− 1.81	− 5.58	− 0.89	− 4.28	− 5.61
1% critical value	− 4.30	− 4.31	− 4.29	− 4.34	− 4.34	− 4.30	− 4.41	− 4.34	− 5.62*
5% critical value	− 3.58	− 3.60	− 3.60	− 3.58	− 3.61	− 3.61	− 3.58	− 3.58	− 3.61
10% critical value	− 3.19	− 3.19	− 3.19	− 3.18	− 3.20	− 3.20	− 3.18	− 3.19	− 3.20
Conclusion	Unstable	Unstable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	Stable

The △ before the variable represents a first-order difference for the variable, $\triangle^2$ represents a second-order difference sequence, C represents a constant term, T represents a time intercept term, K represents the number of lag periods, and * represents a rejection of the original hypothesis at a 1% significance level (the probability of incorrectly rejecting the null hypothesis)

Table 3 Optimal lag order selection

lag	LR	AIC	SC
1	29.38523	14.5885	24.8816
2	20.7896	14.9850	24.8515
3	11.5937	13.1312*	23.4144*

*Represents the optimal lag order selected by the AIC and SC criteria

Construction and testing of econometric models

In order to more intuitively and conveniently analyze the dynamic relationship between EG, EC and CE in Dezhou city, the VAR model is adopted to build a measurement model. VAR model has the advantages of strong flexibility, low parameter requirements, few constraints and convenient modeling. DF test is used to test the stationarity of time series, but considering that DF test is not applicable to a wide range and has many requirements. Therefore, the ADF test method, which is improved on the basis of DF test, is used to test the stationarity of time series. Eviews 7.0 is used to implement the ADF-UR test for each variable, and Table 2 displays the test results.

In Table 2, the ADF values of lnGDP, lnEN, lnCO$_2$, and △lnGDP, △lnEN, and △lnCO$_2$ are all greater than the 1%, 5%, and 10% critical values, which indicates that both the original and first-order difference series of lnGDP, lnEN, and lnCO$_2$ have unit roots. After the second-order difference term higher-order difference treatment of the above three variables, it can be seen that their ADF values are significantly lower than the 1% critical value (the threshold for deciding whether to reject the null hypothesis), i.e., they are significant at the 1% critical value level. Accordingly, it can be judged as I(2) sequence. On the basis of second-order differencing, Johansen cointegration test is carried out so as to test the endogenous cointegration and equilibrium relationship of different independent variables. The ideal lag order is chosen in accordance with the idea of minimising the information value of the AIC and SC criterion, as shown in Table 3.

In Table 3, it can be seen that the optimal lag is 3. Based on this, Table 4's analysis of the cointegration test findings between EG, EC, and CE in Dezhou is shown.

Table 4 Co integration test results between EG, EC, and CE in Dezhou city

Zero hypothesis: number of cointegration vectors	Eigenvalue	Trace statistics (concomitant probability)	5% significance level threshold	Maximum eigenvalue statistic (concomitant probability)	5% significance level threshold
No	0.5408	35.1462*(0.0215)	29.8053	22.2382*(0.0315)	21.0528
Up to 1	0.2610	14.0162(0.0818)	15.5023	7.8623(0.4015)	14.2653
Zero hypothesis: number of cointegration vectors	Eigenvalue	Trace statistics (concomitant probability)	5% significance level threshold	Maximum eigenvalue statistic (concomitant probability)	5% significance level threshold
Up to 2	0.1948	5.8611(0.0162)	3.8408	2.5023(0.1158)	3.8420

*Denying rejection of the original hypothesis at a significance level of 5%

In Tables 3 and 4, it can be seen that there is not a large deviation difference between the three variables, such as Dezhou city EG, EC, and CE. According to the software Eviews 7.0, the cointegration equation between the three variables is obtained, which is shown in Eq. (2).

$$GDP = 1.7854EN + 0.3587CO_2 \qquad (2)$$

In Eq. (2), the energy consumption coefficient 1.7854 indicates that when energy consumption increases by 1 unit, GDP will increase by 1.7854 units, which shows the significant positive impact of energy consumption on economic growth. The increase in energy consumption has promoted the economic development of Dezhou city, indicating that the economic growth of Dezhou city is highly dependent on energy consumption, which may be related to the industrial structure and energy use pattern of Dezhou city, especially in high-energy industries such as industry and manufacturing industry, the increase in energy consumption has directly driven economic activities and output. Carbon emission coefficient 0.3587 indicates that when carbon emission increases by 1 unit, GDP will increase by 0.3587 units, which shows that carbon emission has a positive impact on economic growth, but the impact degree is smaller than that of energy consumption. Although carbon emissions cause environmental pollution, in the short term, increased economic activity (such as industrial production and transportation) also leads to increased carbon emissions, which are reflected in GDP growth. Following that, the mutual influence mechanism between the elements included in the VAR model is examined using the Granger causality test. Equations (3) and (4) display the Granger causality test equations.

$$Y_t = \sum_{j=1}^{m} \alpha_i X_{t-i} + \sum_{i=1}^{m} \alpha_i X_{t-i} + u_t \qquad (3)$$

$$X_t = \sum_{j=1}^{m} \delta_i Y_{t-i} + \sum_{i=1}^{m} \lambda_i X_{t-i} + v_t \qquad (4)$$

Table 5 Granger causality test results of EG, EC and CE in City L

| Null Hypothesis	Lag phase	F statistical value	Significance probability	Conclusion
Glenmorangie distillery reason why $\triangle^2$ EN is not $\triangle^2$ GDP	3	10.7205	0.0001	Reject the original hypothesis
Glenmorangie distillery reason why $\triangle^2$ GDP is not $\triangle^2$ EN	3	0.69730	0.5644	Accept the original assumption
Glenmorangie distillery reason why $\triangle^2$ CO_2 is not $\triangle^2$ GDP	3	9.90857	0.0002	Reject the original hypothesis
Glenmorangie distillery reason why $\triangle^2$ EN is not $\triangle^2$ GDP	3	0.27532	0.8417	Accept the original assumption
Glenmorangie distillery reason why $\triangle^2$ EN is not $\triangle^2$ GDP	3	0.08907	0.4638	Accept the original assumption
Glenmorangie distillery reason why $\triangle^2$ EN is not $\triangle^2$ GDP	3	9.53052	0.0422	Reject the original hypothesis
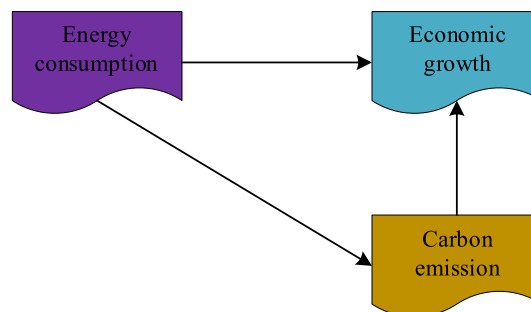
Fig. 6 Causal relationship between EG, EC, and CE

u_t is the random error term in Eq. (3), which represents the part of the fluctuation that the model fails to capture when predicting variable Y_t; v_t is the random error term in Eq. (4), which represents the part of the fluctuation that the model fails to capture at the prediction variable X_t. In time series analysis, the error term is used to capture fluctuations that the model fails to account for, which may result from other factors not included in the model or random perturbations, helping to explain the interaction and dynamic relationships between variables. The Granger causality test results among EG, EC and CE in Dezhou City are shown in Table 5.

As can be seen in Table 5, there is a unidirectional GrgC of EC to EG when the significance level is 5%, while EG is not a GrgC of EC. Therefore, EC in Dezhou city can promote EG, but EG does not significantly exacerbate EC. In addition, when the significance level is 5%, there is a one-way GrgC of CE to EG, while EG is not a GrgC of CE. When the significance level is 5%, there is a one-way GrgC of CE to EG, while EG is not a GrgC of CE. When the significance level is 5 per cent, there is a unidirectional GrgC of EC to CE, while CE is not a GrgC of energy emissions. According to the results of the analysis, there is a causal relationship of "EC → EG", "CE → EG" and "EC → CE" in Dezhou city, as shown in Fig. 6. In Fig. 6, it can be learnt that if excessive attention is paid to energy conservation and emission reduction in Dezhou city, although it can effectively reduce CE and promote environmental protection and
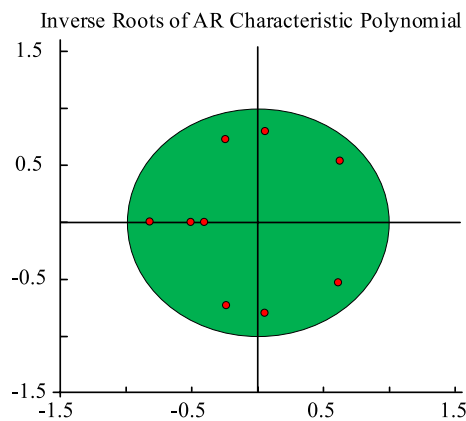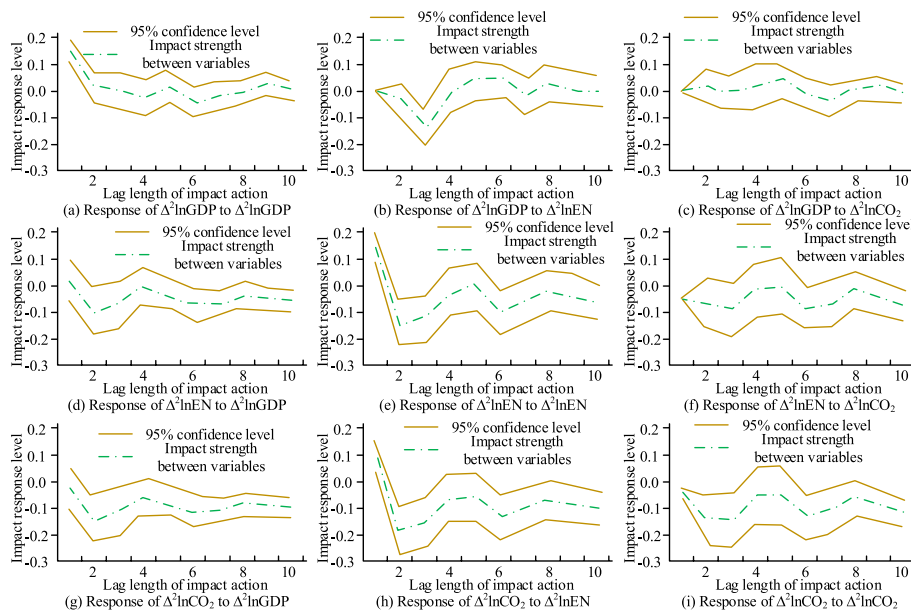
Fig. 7 AR stationarity test

Fig. 8 Pulse response function analysis

sustainable development in Dezhou city, it will affect the economic development of Dezhou city to a certain extent.

In the above, the optimal lag is determined and based on the determined values, the VAR(3) model can be constructed. Prior to that, the VAR model's stability for AR eigen-root smoothness must be checked, and the test results are displayed in Fig. 7. Since the distribution is largely uniform and the inverse of all the characteristic roots in Fig. 7 is less than 1, it can be said that the VAR (3) model has strong stability.

The impulse response function analysis can be performed to examine the dynamic interaction between EC, CE, and EG in Dezhou city after the stability of the VAR model has been demonstrated, as shown in Fig. 8. Figure 8a–i show that there is a smooth positive shock effect of EG on EC, and the intensity of the shock gradually decreases with the growth of time. There is also a smooth positive shock effect of EG on CE, and the

Table 6 Estimation results of VAR (3) Model

-	CO_2	EN	GDP
CO_2(-1)	− 0.014 [− 0.01502]	− 0.858 [− 0.60682]	− 0.738 [− 1.81353]
EN(-1)	0.502 [− 0.83054]	1.308 [− 1.37932]	0.492 [1.77935]
GDP(-1)	− 1.768 [− 4.13532]	− 2.879 [− 4.52537]	0.972 [5.35253]
C	0.312 [2.90052]	0.519 [3.14158]	− 0.038 [− 0.79453]
R-squared	0.978	0.981	0.742
Adj.R.squared	0.980	0.977	0.971

intensity of the shock gradually decreases with the growth of time. The results of the examination of the impulse response function broadly agree with those in Fig. 8.

The estimation results of the VAR (3) model are shown in Table 6. It can be seen that the fit of the regression equations are all high, indicating that the equations are well fitted.

Relevance analysis based on grey correlation and policy recommendations

GCA is a correlation analysis method developed based on grey system theory, which is able to analyse the degree of similarity or dissimilarity between different variables more intuitively, accurately and efficiently, so as to obtain the correlation between different variables. GCA is unique in that it still provides reliable association analysis under small sample conditions, which is especially important for local economic research with limited data. Moreover, GCA does not require that the data must be complete or missing, and can effectively deal with incomplete information systems, which enhances the practicability and reliability of analysis results. In addition, GCA provides an intuitive metric by calculating the correlation coefficient between variables, making the relationship between variables more clear and easy to understand. Therefore, in this study, GCA was used to analyze the internal relationship among variables such as EG, EC and CE in Dezhou City, and traditional econometric models were comprehensively applied to enhance the comprehensibility and accuracy of the analysis. By combining GCA with the traditional econometric model, the causal relationship and dynamic interaction between variables are analyzed while the correlation strength is obtained, so as to provide more empirical suggestions for energy policy, carbon emission control and economic development strategies of Dezhou City. The serial data of the variables in Dezhou city during the period of 2000–2019 are selected, and the data are obtained from the Dezhou City Statistical Yearbook and the Dezhou City Energy Development Report. In the study, these sequences were chosen to comprehensively analyze the effects of EC, energy mix, energy efficiency, industrial structure, and EG on CE. Using the CE of Texas as a reference series, five comparative series of total EC, energy structure, energy efficiency, industrial structure and EG were compared to evaluate their respective contributions to CE. The selection of these sequences, based on their representation of energy use and economic activity, can help identify the impact of different factors on CE and provide a scientific basis for formulating more effective energy conservation and emission

reduction policies. The CE volume of Dezhou city is taken as the reference sequence, which is represented by A. The comparison sequences are total EC $X_1(k)$, energy structure $X_2(k)$, energy efficiency $X_3(k)$, industrial structure $X_4(k)$, and EG $X_5(k)$. 5 comparison sequences are measured by the ratio of total EC accounted for by coal, EC per unit of GDP, the ratio of total output value accounted for by the pillar industry secondary industry, and the total output value of GDP, respectively. Based on the above, Eq. (5) and Eq. (6) can be obtained.

$$X_0(k) = \left\{ X_0(1), X_0(2), \ldots, X_0(k) \right\} \tag{5}$$

$$X_i(k) = \left\{ X_i(1), X_i(2), \ldots, X_i(k) \right\} \tag{6}$$

In Eq. (5) and Eq. (6), k is the number of years of observation and takes the values 1, 2,......, n; i indicates that the factor is the i th. In the data collected by the study, there are large differences in units and magnitudes because different industries and fields will be involved. For this reason, the study has dimensionless all the original series through Eq. (7) and Eq. (8).

$$X_0 = \frac{X_0(k)}{X_0(1)} \tag{7}$$

$$X_i = \frac{X_i(k)}{X_i(1)} \tag{8}$$

The next step is to calculate the correlation coefficient so as to obtain the correlation between the factors of each variable, for the correlation coefficient $\gamma_i(k)$ between $X_0(k)$ and $X_i(k)$ at point k is calculated as shown in Eq. (9).

$$\gamma_i(k) = \frac{\min_i \min_k \left| X_0(k) - X_i(k) \right| + \rho \max_i \max_k \left| X_0(k) - X_i(k) \right|}{\left| X_0(k) - X_i(k) \right| + \rho \max_i \max_k \left| X_0(k) - X_i(k) \right|} \tag{9}$$

In Eq. (9), min and max operations are used to calculate the maximum and minimum deviations between sequences; ρ is the resolution coefficient, with a value range of (0,1), which is used to smooth the calculation and prevent excessive influence of extreme values on the result. Its corresponding grey correlation γ_i is then calculated by Eq. (10).

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \gamma_i(k), k = 1, 2, \ldots, n \tag{10}$$

The larger the value of γ_i, it means that the influence of its corresponding independent variable on the dependent variable is more obvious, i.e. the correlation between the two is stronger. Combining the above, the grey correlation between different independent variables and dependent variables was calculated using the software Eviews, and the results were obtained as shown in Table 7. In Table 7, it can be seen that several variable factors with the highest correlation with the CE of City L, from high to low, are $X_1(k)$, $X_5(k)$, $X_2(k)$, $X_3(k)$, $X_4(k)$. In recent years, the Chinese government has introduced a series of policies on energy structure optimization, CE control, and economic

Table 7 Grey correlation analysis results

Year	$X_1(k)$	$X_2(k)$	$X_3(k)$	$X_4(k)$	$X_5(k)$
2000	1.00000	1.00000	1.00000	1.00000	1.00000
2001	0.99718	0.97968	0.96997	0.98442	0.98281
2002	0.99786	0.94979	0.92140	0.97771	0.94404
2003	0.99066	0.91219	0.87019	0.96774	0.90849
2004	0.99624	0.86869	0.82697	0.90858	0.89212
2005	0.99623	0.84781	0.80140	0.85212	0.87927
2006	0.98862	0.81022	0.76861	0.82372	0.86118
2007	0.99507	0.75496	0.71087	0.78693	0.78827
2008	0.98670	0.73739	0.68114	0.67863	0.76491
2009	0.98959	0.70770	0.64909	0.64276	0.73039
2010	0.98039	0.66086	0.60678	0.57425	0.68202
2011	0.97109	0.62366	0.57046	0.48126	0.64644
2012	0.97293	0.60109	0.54873	0.43473	0.62605
2013	0.96438	0.58076	0.52951	0.39743	0.60419
2014	0.95845	0.56109	0.51152	0.36329	0.58426
2015	0.95859	0.54150	0.49562	0.33475	0.56254
2016	0.9532	0.5403	0.4851	0.3293	0.5518
2017	0.9493	0.5399	0.4864	0.3256	0.5509
2018	0.9453	0.5395	0.4747	0.3201	0.5499
2019	0.9414	0.5359	0.4719	0.3136	0.5489
γ_i	0.98152	0.75417	0.71329	0.70033	0.77424
Logit mixed regression	0.98024	0.75334	0.71452	0.70127	0.77295
Logit random effects	0.98271	0.75276	0.71381	0.70216	0.77461
Poission	0.98365	0.75493	0.71296	0.70103	0.77338

restructuring, and these policy changes can have a significant impact on the study variables and results. First, large-scale clean energy promotion policies at the national level have significantly promoted the development and use of clean energy sources such as wind, solar and biomass. These policy changes may reduce the consumption of traditional fossil energy and promote the green transformation of the energy structure, thereby reducing CE and improving energy efficiency. Secondly, with the launch of the national CE rights trading market, enterprises will conduct CE quota trading through the market mechanism, which will promote the high-emission industries to accelerate the technological upgrading and the implementation of emission reduction measures, which will directly affect the correlation between CE and EG. In addition, the new infrastructure construction and high-tech industry development policies vigorously promoted by the government have promoted the rapid development of the tertiary industry and high-tech industry. These policies are likely to drive a shift in the EG model from resource-intensive to innovation-driven, further optimize the industrial structure, and reduce energy consumption and CEs. These policy changes may make the policy recommendations resulting from the study more relevant.

In addition, the grey correlation between these factors and the CE is more than 0.7, which is much larger than 0.5, which indicates that all of the above mentioned five variable factors have a significant impact on the CE of L-type. Among them, the largest grey correlation value is γ_1, which indicates that it is the total EC that is the most significant

factor influencing the CE of the Dezhou city. This is because during the period from 2000 to 2019, Dezhou City was in a period of rapid economic development and accelerated industrialisation, leading to a sharp increase in EC. In this process, the increase in total EC is inevitable. In addition, during the period from 2000 to 2019, it can be seen that the values of $\gamma_1(k)$ are all greater than 0.95, which to a certain extent can indicate that in order to maintain the national economy and promote the process of industrialisation, the energy demand has been greater. And $\gamma_2(k)$ shows a decreasing trend year by year, which indicates that during the development period, Dezhou city is trying to reduce the proportion of coal consumption, so as to optimise the structure of EC and minimise the CE. However, from the results of the analysis, the energy structure of Dezhou city is still not reasonable enough, which has a greater impact on its CE. The value of γ_5 is ranked the second, which is due to the fact that in the process of economic development, EC is bound to intensify, including the development of industry, public facilities, increase in the number of means of transport, etc., and the increase in CE is therefore unavoidable. The low ranking of γ_3 compared to other factors indicates that during the development period, Dezhou City has taken positive measures to improve energy efficiency. However, energy efficiency is still one of the main factors affecting CE in Dezhou City, which indicates that Dezhou City is not yet energy efficient enough and still needs to continue to work hard. In addition, to prove the reliability of the analysis results, Logit mixed regression model, Logit random effects model and Poission model are further used in Table 7 to conduct robustness test analysis. Through the robustness test of the above three different models, it can be seen that the coefficient values in each model are relatively close and maintain a high correlation degree. This shows that no matter which model is used, the relationship between variables shows strong stability under different statistical methods.

Based on the GCA, the intrinsic links between EC, CE and EG are further analysed, and the results of the previous analyses are combined to give corresponding policy recommendations. Based on the above content, the study gives corresponding policy recommendations to better provide data and theoretical support for local policy making, and take effective measures to balance EC, CE and EG to ensure environmental protection and sustainable development. First of all, we should fundamentally optimize the EC structure, curb high EC industries, and reduce dependence on traditional fossil fuels such as coal. According to the gray correlation analysis results, as shown in Table 7, the correlation between $X_2(k)$ and other variables is more than 0.7, which indicates that coal consumption has a significant impact on EG and CE, so it is particularly important to reduce coal consumption. Efforts should be made to develop, extract and use new energy sources, such as wind, solar and biomass energy, and promote the green transformation of the energy structure by encouraging enterprises and households to use clean energy. At the same time, we will promote energy-efficient technologies and equipment, support enterprises in carrying out energy-saving renovations, and improve energy efficiency. The government should support enterprises to implement energy-saving projects through fiscal subsidies and preferential tax policies, strengthen energy management, and reduce the level of EC per unit of GDP.

Secondly, the gray relational analysis showed that the correlation between $X_3(k)$ and $X_4(k)$ was also high, indicating that EG had a significant effect on CE. Therefore, it is

necessary to find new EG points, increase the proportion of the tertiary industry in the economy, develop modern service industries, high-tech industries and green industries, and promote the transformation of EG from traditional resource-intensive to innovation-driven. In the process of industrial upgrading, we should focus on supporting the development of environmental protection industry and promoting the formation of green economy. In addition, a sound carbon emission monitoring and evaluation system should be established, carbon emission data should be published regularly, and environmental awareness of enterprises and the public should be enhanced. According to the gray correlation analysis, $X_2(k)$ had a high correlation with $X_4(k)$, which indicates that EC is a significant source of CE. To this end, it is necessary to implement a carbon emission trading system, use market mechanisms to promote enterprises to reduce emissions, formulate strict carbon emission standards, punish enterprises that exceed the standard of emissions, and promote the application and promotion of low-carbon technologies.

Although GCA has unique advantages in revealing the relationship between variables, it also has certain limitations. First of all, GCA has high requirements on the integrity and accuracy of data. If there is a large error or incomplete data, the accuracy of the calculation results of correlation degree will be affected, thus affecting the research conclusion. Secondly, grey correlation analysis simplifies the internal mechanism of complex systems to a certain extent, and may ignore some potential important factors, resulting in insufficient analysis results, which need to be integrated with other analysis methods for comprehensive verification. In addition, grey correlation analysis mainly focuses on static correlation, and its ability to reveal dynamic changes and causality between variables is limited. Therefore, the research conclusions still need to be interpreted carefully, and further verified and improved in practice.

Conclusion

The study uses the historical data of Dezhou city as an example and combines the 3E theory and the EKC curve theory to create a VAR model for the factors of EC, emissions of greenhouse gases, and carbon dioxide (CE) in Dezhou city. It then determines the correlation and the mutual influence mechanism of the three factors using techniques like ADF-UR, GrgC, and GCA. The analysis results show that the ADF values of lnGDP, lnEN, lnCO$_2$, and △lnGDP, △lnEN, △lnCO$_2$, etc. are all greater than the critical values of 1%, 5%, and 10%, which indicates that the original and first-order difference series of lnGDP, lnEN, and lnCO$_2$ have unit roots, and that there are not large deviations, but rather a long-term balanced and stable cointegration relationship. The results of impulse analysis show that there is a causal relationship of "EC → EG", "CE → EG" and "energy consumption → CE" in L. The fit of the regression equations of the VAR (3) model are all high, indicating that the equations are well fitted. The fit of the regression equations is high, indicating that the equations are well fitted. The GCA results show that the variables with the highest correlation with CE in Dezhou city are $X_1(k)$, $X_5(k)$, $X_2(k)$, $X_3(k)$, $X_4(k)$ in descending order. The report concludes by making appropriate policy recommendations based on the analysis' findings, including strengthening the EC structure, optimising the industrial structure, and promoting a low-carbon lifestyle. The study can serve as a point of reference for the implementation of green, environmental protection,

and sustainable development policies for the city of L's economy and can also offer some suggestions for the growth of the green economy in other Chinese cities. Although this study has achieved some valuable conclusions, it also has some limitations. First of all, the research mainly adopts VAR model and GCA. Although these methods have advantages in analyzing variable relationships, they still have certain limitations in revealing complex dynamic changes among variables. Future studies may consider introducing more dynamic econometric models to analyze the dynamic relationship between variables more comprehensively. Second, although GCA can effectively handle small samples and incomplete information, its results still depend on the integrity and accuracy of the data. To improve the robustness of the analysis, future studies can be combined with other methods, such as Bayesian methods or machine learning algorithms, to enhance the reliability of the results. In conclusion, future studies should be further improved in terms of methodological diversity and comprehensiveness of analysis, so as to provide more accurate and comprehensive policy recommendations to help local governments promote green and sustainable development while achieving economic growth.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares that there is no conflict interests.

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