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RESEARCH ARTICLE

China's 2060 carbon-neutrality agenda: the nexus between energy consumption and environmental quality

Kaodui Li[1,2,3] · Hongxin Ying[1] · Yi Ning[1] · Xiangmiao Wang[1] · Mohammed Musah[4] · Muntasir Murshed[5,6] · Morrison Alfred[7] · Yanhong Chu[1] · Han Xu[1] · Xinyi Yu[1] · Xiaxin Ye[1] · Qian Jiang[1] · Qihe Han[1]

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Abstract

This study examined the nexus between energy consumption and environmental quality in light of China's 2060 carbon-neutrality agenda utilizing annual frequency data from 1971 to 2018. In order to obtain valid and reliable outcomes, more robust econometric techniques were employed for the analysis. From the results, all the variables were first differenced stationary and cointegrated in the long-run. The elastic effects of the predictors on the explained variable were explored through the ARDL, FMOLS, and the DOLS techniques, and from the discoveries, energy utilization worsened environmental quality in the country via more CO_2 emissions. Also, industrialization and urbanization deteriorated the country's environmental quality; however, technological innovations improved ecological quality in the nation. On the causal connections between the variables, a unidirectional causality from energy consumption to CO_2 effluents was discovered. Also, feedback causalities between industrialization and CO_2 secretions, and between urbanization and CO_2 exudates were disclosed. However, there was no causality between technological innovations and CO_2 emanations. Based on the findings, the study recommended among others that, since energy consumption pollutes the environment, the country should transition to the utilization of renewable energies. Also, the government should allocate more resources to the renewable energy sector. This will help increase the portion of clean energy in the country's total energy mix. Furthermore, research and developments that are linked to the utilization of green energies should be supported by the government. Data constraints were the main limitation of this exploration. Therefore, in the future, if more data become available, similar explorations could be conducted to check the robustness of our study's outcomes.

Keywords Energy consumption · Environmental quality · Industrialization · Technological innovations · Urbanization · China

Abbreviations

EC	Energy consumption
IND	Industrialization
URB	Technological innovations
EQ	Environmental quality
CO_2 emissions	Carbon dioxide emissions
DARDL	Dynamic autoregressive distributed lag
ARDL	Autoregressive distributed lag
VECM	Vector error correction model
GMM	Generalized method of moments
AMG	Augmented mean group

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✉ Mohammed Musah
mmusah@gctu.edu.gh

[1] School of Finance and Economics, Jiangsu University, Zhenjiang, People's Republic of China

[2] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing, People's Republic of China

[3] Division of State-Owned Enterprise Reform and Innovation, Institute of Industrial Economics, Jiangsu University, Zhenjiang, People's Republic of China

[4] Department of Accounting, Banking and Finance, School of Business, Ghana Communication Technology University, Accra, Ghana

[5] School of Business and Economics, North South University, Dhaka-1229, Bangladesh

[6] Department of Journalism, Media and Communications, Daffodil International University, Dhaka, Bangladesh

[7] Department of Accounting Studies Education, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Kumasi, Ghana

CS-ARDL	Cross-sectional autoregressive distributed lag
ECT	Error correction term
ADF	Augmented Dickey-Fuller
PP	Phillips-Perron
WDI	World Development Indicators
FMOLS	Fully modified ordinary least squares
DOLS	Dynamic ordinary least squares
OVB	Omitted variable bias
SDGs	Sustainable development goals
OECD	Organisation for Economic Co-operation and Development
PCA	Principal component analysis
SD	Standard deviation
VIF	Variance inflation factor
GHG	Greenhouse gas
EFP	Ecological footprint
QQR	Quantile on quantile regression
SGC	Spectral Granger causality
MINT	Mexico Indonesia Nigeria Turkey
MENA	Middle East and North Africa
ASEAN	Association of South East Asian Nations
EU-28	European Union-28
LASSO	Least absolute shrinkage and selection operator
PMG	Pooled mean group
REC	Renewable energy consumption
NREC	Non-renewable energy consumption
CCEMG	Common correlated effects mean group
OLS	Ordinary least squares
FE	Fixed effects
US	United States
BEC	Biogas energy consumption
NARDL	Non-linear autoregressive distributed lag
AIC	Akaike information criterion
SIC	Schwarz information criterion

Introduction

The main ambition of most nations in recent times is to reduce the environmental implications of greenhouse gas (GHG) emissions which have resulted in global warming and climate change (Musa et al. 2021; Li et al. 2021). As a result, it has become imperative for the world economies to adopt policies that can enable them to decouple economic growth and environmental pollution (Qin et al. 2021). China as the leading emitter of carbon is under severe pressure to mitigate its CO_2 emissions (Ma et al. 2021; Yao and Zhang 2021; Liu et al. 2021; Xiaosan et al. 2021). As a signatory to the Paris Agreement (2015), Kyoto Protocol. (2005), Copenhagen Accord. (2009), and other international treaties, the country has initiated various environmental regulations and energy utilization strategies to help minimize the consumption of fossil fuels and other conventional energies that deteriorate its ecological quality (Yuelan et al. 2019; Li et al. 2021). By the year 2030, China aims to curtail its CO_2 effusions by 65% from the 2005 figure and promote the utilization of clean energies by about 25% (Yao and Zhang 2021; Li et al. 2021). Also, the government of China has the 2060 carbon-neutrality agenda which is one of its emission reduction strategies to help the nation attain become carbon neutral (Ahmad et al. 2019, 2018; Zeraibi et al. 2021; Rehman et al. 2021b). If China is able to meet its emission reduction targets, then, the world's ambition of minimizing global warming and climate change would receive a major boost, because of the country's dominance in global CO_2 effluents.

According to Lauri (2021), China's CO_2 effusions increased by approximately 1.7% per year on average from 2015 to 2019. Irrespective of the economic consequences of the COVID-19 pandemic, the country's CO_2 exudates continued to surge by about 1.5% in 2020. Overall, power generation by fossil fuels rose by 2.5% in 2020 compared to 2019 (China Electricity Council 2020). Moreover, production by industries accounted for 66% of the country's total energy utilization and around 50% of its total emissions (China National Bureau of Statistics 2020). In 2019, steel and cement production surged by 7%, while noncombustion process-related emanations rose by 5.6%. Thus, industrial emissions are currently moving upwards, with productions from steel and cement being the dominant factors (Mikhail and Kate 2020). Though China has improved on its green energy generation, the share of solar, wind, and other clean sources of energies represent less than 10% of its total energy mix (China National Bureau of Statistics 2020). Besides, the nation's economic recovery policies have been carbon-intensive, leading to the rise in fossil fuel power generation, coal mining output, and industrial coal utilization, resulting in more pollution (Lauri 2020). Therefore, shifting from this current energy profile to one focused on emission mitigations warrants a lot of efforts from the Chinese government.

Numerous explorations have focused on the linkage between energy consumption (EC) and environmental quality (EQ) in China. For example, Xiangmei et al. (2018) study on China affirmed EC as detrimental to EQ in the country. Also, Marques et al.'s (2021) investigation discovered CO_2 effusions as a driver of EC in the nation. Moreover, Yiping's (2021) exploration confirmed electricity from renewable sources as beneficial to ecological quality in the country. According to Ma et al. (2019), industrial energy utilization was the main determinant of environmental pollution in the country. Wang et al.'s (2021) study discovered energy from dirty sources as a trivial predictor of EQ in the nation. Also, Dong et al.'s (2018) analysis revealed green energy as harmless to EQ in the country. To Rong et al. (2020), electricity consumption explained more that 75% of CO_2 effusions in the country. Moreover, Jian et al.'s (2019) study found EC as damaging to EQ in China. All the above explorations were conducted on China, but their findings are conflicting. The contrasting discoveries might be as a result of the methodologies employed, the time dimension or the studied variables among others. This suggests that the EC and EQ debate is far from over and demands more interrogations. Therefore, undertaken this research to come out with policy options to help China attain its sustainable development goals (SDGs) was deemed fitting. The main motivation of this study was to help China become carbon–neutral. According to a 2018 report of the Intergovernmental Panel on Climate Change, attaining global warming of 1.5 °C in 2030 will demand that global CO_2 emanations reduce by 45% from 2010, reaching a net zero around 2050, while attaining global warming of 2 °C in 2030 will demand that global CO_2 effluents reduce by 25% from 2030, reaching a net zero around 2070. Therefore, if China should wait until 2030 before they take carbon-neutrality actions, their global emission ambitions cannot be accomplished. Hence, a study to help the Chinese government to improve its CO_2 effusions mitigation strategies was deemed appropriate.

The contributions of this exploration are in threefold. First, the study contributed methodologically by following a well-outlined analytical process. At the initial stage, stationarity tests were undertaken to examine the variables' integration order. Afterwards, tests to check the cointegration attributes of the series were conducted. At the third phase, the elastic effects of the covariates on the response variable were explored. Finally, a causality test was undertaken to determine the path of causations amidst the series. Most prior explorations on the EC and EQ connection failed to follow a well-outlined econometric strategy. Secondly, the issue of omitted variable bias (OVB) is not been recognized by most studies on the connection between EC and EQ. This is disadvantageous because OVB could yield prejudiced and unreliable coefficient values, which could lead to erroneous inferences (Musah et al. 2021a, b, c; Li et al. 2020a, b). This study therefore controlled for industrialization (IND), technological innovations (TI), and urbanization (URB) to help minimize OVB issues. Finally, our exploration adopted the time series approach, which completely varies from other prior investigations on the topic of concern. This approach was used because it helps to improve the power of statistical tests leading to more robust outcomes. Most prior investigations on the studied topic adopted different approaches and might have failed to capture the true relationship amidst the series.

The significance of this exploration cannot be underrated. First, the recommendations of this study will help the Chinese government to adopt renewable and other energy utilization alternatives that will help boost ecological quality in the country. The study is also essential because it will help policymakers to implement other effective policy interventions that are required to minimize climate change and its repercussions. The study is finally vital in that it adds to the existing literature on the linkage between EC and EQ. This will serve as a reference material for future studies on the topic of concern. This paper is original because, its goal is clearly stated; the methodologies used are extensive; the findings are well reported, evaluated, and debated; and the policy suggestions are well-thought-out. This paper is grouped into five sections. The "Introduction" section is the introduction of the study, while the "Literature review" section outlines literature that supports the issue at hand. The "Materials and methods" section is on the methodology, while the "Results of the study" section displays the study's results and discussions. Finally, the "Conclusions and policy recommendations" section presents the conclusions, recommendations, and study limitations.

Literature review

In this section, literature that are related to the topic are reviewed. The reviews are categorized into two. The first part reviews literature on the nexus between EC and EQ in China, while the second part presents reviews on the connection between EC and EQ in other parts of the world. On the linkage between EC and EQ in China, Rahman and Vu's (2021) research discovered a positive association between EC and ecological pollution in the country. Also, the VECM Granger causality found a one-way causality from CO_2 secretions to EC in the nation. Yao and Zhang (2021) also studied the connection between EC and EQ in China by employing the ARDL estimator. From the revelations, clean energy enhanced EQ in the country. Zheng et al. (2020) researched on China from the period 1978. From the results, the influence of energy intensity slowed the growth of CO_2 effusions in the country. Shum et al. (2021) analyzed the determinants of EQ in China by employing the LASSO model. From the results, EC was a main driver of CO_2 exudates. Xiangmei et al. (2018) undertook a study on China from 1953 to 2016. From the results, EC surged CO_2 effusions in the country. Khan et al. (2021a, b, c, d) explored the beta decoupling relationship between EC and

CO_2 excretions. From the results, EC was one of the factors that caused CO_2 emissions to rise in the country.

Marques et al. (2021) studied China from 1977 to 2016. From the results, CO_2 effusions drove energy consumption in the country. Yiping (2021) studied China from 1988 to 2018 and disclosed that electricity from renewable sources limited environmental pollution in the country. Wang et al. (2021) investigated the drivers of ecological footprint (EFP) in China over a 36-year period. The ARDL approach was engaged to determine the coefficients of the predictors. From the discoveries, energy from dirty sources was not a material predictor of EQ in the country. Alola et al. (2021) researched on China from 1971 to 2016. Based on the QQR estimates, fossil fuel and primary energy utilization impacted positively on EFP in all quantiles. Amazingly, clean energy utilization also exerted a positive influence on EFP in the country. Finally, the spectral Granger causality (SGC) discovered a causation from primary energy use to EFP and from clean energy to EFP. Zou and Zhang (2020) examined the connection between EC and EQ in China from 2000 to 2017. From the results, EC and EQ were interrelated as a feedback causality between the two series was observed. Tong et al. (2020) conducted a study on E7 countries by employing the ARDL technique. From the revelations, a short-run causality from EC to CO_2 effluents in China was found. Li et al. (2021), Li et al. (2021), Li et al. (2021), Li et al. (2021), Li et al. (2021) investigated the linkage between energy structure and EQ in 30 Chinese provinces from 2011 to 2017. From the discoveries, energy structure based on coal had a substantial effect on emissions in the country. Jiang et al. (2019) undertook a study on China from 1982 to 2017. From the results, EC surged ecological pollution in the country.

Numerous explorations on EC and EQ in other parts of the world have also been conducted with contrasting discoveries. For example, Agbede et al. (2021) investigated MINT countries over the period 1971 to 2017. The ARDL-PMG results of the study revealed a positive association between EC and environmental pollution. Also, a causality from EC to ecological pollution was unfolded. Ahmad et al. (2021a, b) investigated 11 developing economies from 1992 to 2014. From the discoveries, a surge in electricity consumption minimized environmental pollution in the economies. The finding implies country-specific policies should be undertaken to help stimulate EQ in the economies. Qayyum et al. (2021) analyzed the nexus between EC and EQ in India from 1980 to 2019. From the ARDL estimates, REC improved EQ in the nation. Khan et al. (2020) researched on Pakistan from 1990 to 2015. From the ARDL estimates, access to electricity worsened EQ via high CO_2 emanations. Shobande and Ogbeifun (2021) analyzed the nexus between EC and EQ in OECD countries from 1980 to 2019. From the results, EC promoted ecological pollution in the nations. Kirikkaleli and Adebayo (2021a) studied the connection between EC and EC in India from 1990Q1 to 2015Q4. From the results, REC was beneficial to EQ in the country. Also, REC caused consumption-based CO_2 effusions at different frequency levels. Chien et al. (2021) researched on top Asian economies from 1990 to 2017. Based on the CS-ARDL estimates, REC improved EQ in the economies; however, NREC spurred environmental pollution in the economies. Khan et al. (2021a, b, c, d) analyzed the linkage between EC and EQ in 21 developing economies from 1970 to 2018. The study employed the OLS, FE, and the GMM regression techniques in its analysis. From the discoveries, REC improved EQ in the economies; however, NREC was not friendly to the ecologies of the nations.

Khan et al. (2021a) assessed the connexion amidst EC and ecological pollution in 188 countries from 2002 to 2018. From the OLS, FE, GMM and the system GMM estimates, NREC escalated environmental pollution in the nations; however, REC was friendly to the countries' environment. Xue et al. (2021) examined the linkage between EC and EQ in South Asian economies by employing recently developed econometric techniques. From the discoveries, REC improved EQ in the economies; however, NREC deteriorated ecological quality in the economies. Khan et al. (2021b) investigated the association between EC and environmental pollution in 180 economies from 2002 to 2019. From the OLS, FE and system GMM discoveries, REC reduced ecological pollution in the economies. Khan et al. (2021c) used a global panel to investigate the determinants of EQ from 2002 to 2019. From the two-step system GMM results of the study, REC enhanced EQ in the countries. Bekun et al. (2021) researched on SSA and discovered from the PMG econometric technique that conventional energy harmed EQ in the countries; however, clean energy improved the countries' EQ. Bibi et al. (2021) investigated the linkage between biomass EC and EQ in the US from 1981M01 to 2019M12. From the revelations, a causation from BEC to CO_2 effluents was discovered. Ali et al. (2021) undertook a study on Nigeria from 1981 to 2014. Based on the DARDL results, EC spurred CO_2 excretions in the nation. Iqbal et al. (2021) explored the asymmetric effects of clean energy on CO_2 effusions in Pakistan. The NARDL technique was used to determine the parameters of the covariates. From the results, positive changes in clean energy generation promoted CO_2 exudates in the country; however, negative changes in clean energy generation mitigated CO_2 secretions in the nation. Ahmad et al. (2021a, b) investigated 11 developing economies from 1992 to 2014. The FMOLS and the PMG techniques were employed for the parameter estimations, and from the findings, electricity consumption mitigated environmental pollution in the economies. Also, a feedback causation amidst electricity consumption and CO_2 exudates was established.

Baydoun and Aga (2021) studied the linkage between EC and EQ in GCC economies from 1995 to 2018. From the CS-ARDL estimates, EC worsened EQ in the countries via high CO_2 excretion. Also, a causality from EC to CO_2 effluents was disclosed. Nawaz et al. (2021) analyzed the impasse of EC on EQ in South Asian economies from 1990 to 2017. Based on the FMOLS estimates, EC minimized EQ in the countries. Khurshid et al. (2021) investigated the association between EC and EQ in Western and Southern Europe from 2000 to 2018. The NARDL and the OLS approaches were engaged for the parameter estimations. From the discoveries, EC was a key polluter in the economies. Chunyu et al. (2021) researched on 18 countries from 2010 to 2019 and disclosed that energy from dirty sources mitigated EQ in the countries; however, energy from clean sources improved EQ in the nations. Musa et al. (2021) investigated the EC and EQ connection in EU-28 countries from 2002 to 2014. From the two-step GMM discoveries of the study, REC was positively related to environmental performance in the nations. Balli et al. (2020) researched on Turkey from 1960 to 2014. Based on the VECM output, a causation from EC to CO_2 exudates was confirmed. Osobajo et al. (2020) analyzed the association between EC and EQ in 70 economies from 1994 to 2013. Findings of the study confirmed EC as detrimental to EQ in the countries. Also, a one-directional causality from EC to CO_2 excretions was unfolded. Alharthi et al. (2021) investigated the link between EC and EQ in MENA countries from 1990 to 2015. From the discoveries, REC mitigated ecological pollution in the countries, but NREC worsened environmental pollution in the economies. Chontanawat (2020) explored the linkage between EC and CO_2 emanations in ASEAN region from 1971 to 2015. From the results, EC was materially related to environmental pollution in the region. All the aforestated studies are on the connection between EC and EQ; however, their findings are contradictory. The conflicting outcomes might be as a result of the methodologies employed, the time dimension or the studied variables among others. This suggests that the EC and EQ argument is unceasing and warranted further investigations. Therefore, a study on the linkage between EC and EQ in China was worthwhile.

Materials and methods

Data source and descriptive statistics

A time series data of China for the period 1971 to 2018 was used for the study. The study period was chosen based on data availability. For instance, there was no data available for the proxy of environment quality (CO_2 emissions) after 2018. Also, data for energy consumption was not available from 1960 to 1970 and after 2014. Therefore, using the explained variable as the determining factor, the period 1971 to 2018 was deemed appropriate. This implies the data used for the analysis was not balanced. Further details on the series are outlined in Table 1. The descriptive statistics of the series are displayed in Tables 2 and 3. From the table, IND was the highest in terms of average values, while TI was the lowest. Also, TI was the most volatile based on the SD values, while URB was the least volatile. From the skewness results, the distribution of TI was negatively skewed, while that of the rest was positively skewed. The kurtosis outcomes also confirmed the distribution of TI to be leptokurtic in shape, while that of the rest was platykurtic in shape. Additionally, the covariates were not highly collinear based on the multi-collinearity test results. Finally from the PCA results indicated in Table 4, the predictors had higher

Table 1 Variable description and measurement units

Variable	Measurement unit	Source
Environmental quality (CO_2 emissions)	Metric tons per capita	WDI (2021)
Energy consumption (EC)	Kg of oil equivalent per capita	WDI (2021)
Industrialization (IND)	Industry (including construction), value added (constant 2010 US$)	WDI (2021)
Technological innovation	Resident and nonresident patent applications	WDI (2021)
Urbanization (URB)	Urban population (% of total population)	WDI (2021)

Table 2 Descriptive statistics and correlational matrix

Descriptive statistics					
Statistic	$lnCO_2$	lnEC	lnIND	lnTI	lnURB
Mean	0.955	6.764	26.706	0.254	3.378
Median	0.893	6.642	26.634	0.939	3.371
Maximum	2.023	7.713	28.999	1.822	4.016
Minimum	0.041	6.142	24.659	− 10.012	2.844
Std. dev	0.603	0.472	1.398	1.921	0.388
Skewness	0.393	0.703	0.081	− 3.644	0.079
Kurtosis	2.098	2.369	1.674	19.435	1.685
Jarque–Bera	2.682	4.454	3.344	6.056	3.288
Probability	0.262	0.108	0.188	0.231	0.193
Correlational matrix					
Variable	$lnCO_2$	lnEC	lnIND	lnTI	lnURB
$lnCO_2$	1.000				
lnEC	0.791 (0.000)***	1.000			
lnIND	0.878 (0.000)***	0.563 (0.043)**	1.000		
lnTI	0.676 (0.000)***	0.623 (0.076)*	0.691 (0.000)***	1.000	
lnURB	0.781 (0.000)***	0.459 (0.000)***	0.698 (0.000)***	0.385 (0.057)*	1.000

***, **, * denote significance at the 1%, 5%, and the 10% levels correspondingly.

Table 3 Multi-collinearity tests results

	VIF and tolerance tests		Farrar and Glauber test	
Variable	VIF	Tolerance	*F* test	*p* value
lnEC	2.39	0.418	4.022	0.008***
lnIND	2.93	0.341	5.774	0.037**
lnTI	2.02	0.495	3.098	0.072*
lnURB	2.52	0.397	2.979	0.005***
Mean VIF	2.47	-	-	-

VIF variance inflation factor while ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively.

Table 4 Principal component analysis

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp 1	2.382	1.314	0.596	0.596
Comp 2	1.068	0.719	0.267	0.863
Comp 3	0.34[illegible]	0.148	0.087	0.950
Comp 4	0.201	-	0.050	1.000
Principal components (eigenvectors)				
Variable	Comp 1	Comp 2		
lnEC	0.514 ^{m}	− 0.322		
lnIND	0.529 ^{m}	− 0.198		
lnTI	0.422	0.902 ^{n}		
lnURB	0.528 ^{m}	− 0.209		

^{m}denotes significant loadings under comp 1, while ^{n}represents significant loadings under comp 1.

loadings and were, therefore, appropriate to predict the emanation of CO_2 in the country.

Model specification

This study examined the link between energy consumption (EC) and environmental quality (proxied by CO_2 emanations) in China, while controlling for industrialization (IND), technological innovation (TI), and urbanization (URB). In achieving this goal, the following econometric model was proposed:

$$CO_{2it} = \alpha_i + \beta_1 EC_{it} + \beta_2 IND_{it} + \beta_3 TI_{it} + \beta_4 URB_{it} + \mu_{it} \quad (1)$$

where CO_2 is the response variable representing environmental quality (EQ) and EC is the main explanatory variable of concern. Also, β_1,β_2,β_3, and β_4 are the parameters of the regressors, while α_i is the constant term. Moreover, μ_{it} is the error term, while i and t denote the country and time respectively. To help reduce heteroscedasticity issues, natural logarithm was taken on both sides of Eq. 1. The resulting log-linear model therefore became;

$$lnCO_{2it} = a_i + \beta_1 lnEC_{it} + \beta_2 lnIND_{it} + \beta_3 lnTI_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (2)$$

where $lnCO_2$ is the logarithm of the explained variable, while *lnEC*, *lnIND*, *lnTI*, and *lnURB* are the log conversions of the explanatory variables. After transforming the variables into natural logarithms, the coefficients could be interpreted as elasticities. The study expected EC to have a positive influence on CO_2 effusions ($\beta_1 > 0$), if residential and nonresidential energies consumed in the countries are carbon-intensive. Otherwise, EC was to exert a negative effect on CO_2 exudates ($\beta_1 < 0$), if energies consumed in the country were from clean sources that could help to boost EQ in the nation ($\beta_2 < 0$). Also, IND was to positively influence CO_2 effluents ($\beta_1 > 0$), if the energies utilized at the industrial level in the country were not environmentally friendly. Otherwise, IND was to negatively impact the emissivities of CO_2 in the nation ($\beta_2 < 0$), if IND was linked to the use of green energy. Additionally, TI was to mitigate the emanation of CO_2 in the country ($\beta_3 < 0$) because it promotes less polluting activities in an economy. Finally, URB was to have a positive impact on CO_2 emittance ($\beta_4 > 0$), if URB led to the utilization of polluting energies in the country both domestically and industrially. Otherwise, URB was to negatively affect CO_2

excretions ($\beta_4 < 0$), if the migration of people to big cities in China resulted in the utilization of green energy.

Analytical process

To comprehensively examine the EC-EQ linkage in China, a four-staged econometric procedure was followed. Firstly, the ADF and the PP tests for unit root were conducted to examine the integration order of the variables. Afterwards, following Murshed (2021), the ARDL bound test and the Johansen test were performed to check the cointegration attributes of the series. Following Pesaran et al. (2001), the ARDL bound test specification for this study is expressed as;

is the parameter of the ECT. For robustness purpose, the FMOLS and the DOLS estimators were also adopted. These estimators were adopted because they mitigate issues of heteroscedasticity (Kiefer and Vogelsang 2002). The techniques are also advantageous because they are vigorous to endogeneity and autocorrelation in regression analysis (Funk and Strauss 2000). The FMOLS estimator is specified as;

$$\hat{\beta}_{FMOLS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(r_{it}-\bar{r}_i)^2\right)\right]^{-1} \times \left[\left(\sum_{t=1}^{T}(r_{it}-\bar{r}_i)\hat{h}_{it} - T\hat{\Delta}_{eu}\right)\right], \quad (6)$$

In Eq. 6, r and h symbolize the regressors and the regressand correspondingly, while Δ_{eu} is the covariance term. Also, $\hat{\Delta}_{eu}$ is the estimated value of the covariance term,

$$\Delta \ln CO_{2t} = \varphi_0 + \varphi_1 CO_{2t-1} + \varphi_2 \ln EC_{t-1} + \varphi_3 \ln IND_{t-1} + \varphi_4 \ln TI_{t-1} + \varphi_5 \ln URB_{t-1} + \sum_{i=1}^{p}\beta_{1i}\Delta CO_{2t-1} + \sum_{i=1}^{q}\beta_{2i}\Delta \ln EC_{t-1} + \sum_{i=1}^{q}\beta_{3i}\Delta \ln IND_{t-1} + \sum_{i=1}^{q}\Delta \ln TI_{t-1} + \sum_{i=1}^{q}\beta_{5i}\Delta \ln URB_{t-1} + u_t \quad (3)$$

where the change operator is denoted by Δ, the optimal lags selected via the AIC is represented by *t-1*, and the estimated parameters are denoted by φ and β. It should be noted that the Johansen cointegration test was employed to authenticate the bound test results. This test is advantageous because it can detect multiple cointegrating vectors (Johansen 1991). At the third phase of the analysis, the elasticities of the predictors were first estimated via the ARDL approach. This method was adopted because it produces valid results even in short-time datasets. Also, if the integration order of investigated series is mixed, the estimator can still produce vigorous results (Khan et al. 2021b). The ARDL model developed to explore the long-run connections amidst the variables is specified as;

$$lnCO_{2t} = \alpha_0 + \sum_{i=1}^{p}\sigma_{1i} lnCO_{2t-1} + \sum_{i=1}^{q}\sigma_{2i} lnEC_{t-1} + \sum_{i=1}^{q}\sigma_{3i} lnIND_{t-1} + \sum_{i=1}^{q}\sigma_{4i} lnTI_{t-1} + \sum_{i=1}^{q}\sigma_{5i} lnURB_{t-1} + u_t \quad (4)$$

where σ denotes the long-term variance in the variables and q represents the lags selected through the AIC. The short-run ARDL model for the exploration is expressed as;

$$lnCO_{2t} = \alpha_0 + \sum_{i=1}^{p}\sigma_{1i}\Delta lnCO_{2t-1} + \sum_{i=1}^{q}\sigma_{2i}\Delta lnEC_{t-1} + \sum_{i=1}^{q}\sigma_{3i}\Delta lnIND_{t-1} + \sum_{i=1}^{q}\sigma_{4i}\Delta TI_{t-1} + \sum_{i=1}^{q}\sigma_{5i}\Delta lnURB_{t-1} + \phi ECT_{t-1} + u_t \quad (5)$$

where the variance of the short run is symbolized by σ, the error correction term is represented by ECT_{t-1}, and ϕ

while T and N are the time frame and the dimension of the data respectively. The DOLS estimator on the other hand is expressed as;

$$\hat{\beta}_{DOLS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}\left(R_{it}R'_{it}\right)\right)\left(\sum_{t=1}^{T}\left(R_{it}\tilde{h}_{it}\right)\right)\right]^{-1} \quad (7)$$

where R epitomizes the set of predictors that are $2(k+1)\times 1$ and $R_{it} = \left(r_{it}-\bar{r}_i, \Delta r_{it-k}, \ldots, \Delta r_{it+K}\right) - K$ is the number of covariates. Finally, the VECM of Engle and Granger (1987) was engaged to examine causations amidst the series. This estimator was adopted because it yields consistent and reliable results in time series analysis. The test began by first estimating Eq. 2 to recover residuals considered as lagged error correction terms (ECT). Afterwards, the ensuing dynamic error correction models were estimated to unravel the causalities amid the series;

$$\Delta lnCO_{2t} = \omega_1 + \sum_{j=1}^{q}\varphi_{1,1j}\Delta lnCO_{2t-j} + \sum_{j=1}^{q}\varphi_{1,2j}\Delta lnEC_{t-j} + \sum_{j=1}^{q}\varphi_{1,3j}\Delta lnIND_{t-j} + \sum_{j=1}^{q}\varphi_{1,4j}\Delta lnTI_{t-j} + \sum_{j=1}^{q}\varphi_{1,5j}\Delta lnURB_{t-j} + \varnothing_1 ECT_{t-1} + \mu_{1,t} \quad (8)$$

$$\Delta EC_t = \omega_1 + \sum_{j=1}^{q}\varphi_{1,1j}\Delta lnEC_{t-j} + \sum_{j=1}^{q}\varphi_{1,2j}\Delta lnCO_{2t-j} + \sum_{j=1}^{q}\varphi_{1,3j}\Delta lnIND_{t-j} + \sum_{j=1}^{q}\varphi_{1,4j}\Delta lnTI_{t-j} + \sum_{j=1}^{q}\varphi_{1,5j}\Delta lnURB_{t-j} + \varnothing_1 ECT_{t-1} + \mu_{1,t} \quad (9)$$

$$\Delta IND_t = \omega_1 + \sum_{j=1}^{q} \varphi_{1,1j} \Delta lnIND_{t-j} + \sum_{j=1}^{q} \varphi_{1,2j} \Delta lnEC_{t-j} + \sum_{j=1}^{q} \varphi_{1,3j} \Delta lnCO_{2t-j} + \sum_{j=1}^{q} \varphi_{1,4j} \Delta lnTI_{t-j} + \sum_{j=1}^{q} \varphi_{1,5j} \Delta lnURB_{t-j} + \varnothing_1 ECT_{t-1} + \mu_{1,t} \quad (10)$$

$$\Delta TI_t = \omega_1 + \sum_{j=1}^{q} \varphi_{1,1j} \Delta lnTI_{t-j} + \sum_{j=1}^{q} \varphi_{1,2j} \Delta lnIND_{t-j} + \sum_{j=1}^{q} \varphi_{1,3j} \Delta lnEC_{t-j} + \sum_{j=1}^{q} \varphi_{1,4j} \Delta lnCO_{2t-j} + \sum_{j=1}^{q} \varphi_{1,5j} \Delta lnURB_{t-j} + \varnothing_1 ECT_{t-1} + \mu_{1,t} \quad (11)$$

$$\Delta URB_t = \omega_1 + \sum_{j=1}^{q} \varphi_{1,1j} \Delta lnURB_{t-j} + \sum_{j=1}^{q} \varphi_{1,2j} \Delta lnTI_{t-j} + \sum_{j=1}^{q} \varphi_{1,3j} \Delta lnIND_{t-j} + \sum_{j=1}^{q} \varphi_{1,4j} \Delta lnEC_{t-j} + \sum_{j=1}^{q} \varphi_{1,5j} \Delta lnCO_{2t-j} + \varnothing_1 ECT_{t-1} + \mu_{1,t} \quad (12)$$

In the equations above, q denotes the lags determined via the SIC, while ω signifies the intercepts. Also, φ denotes the coefficients to be estimated, while μ is the error term. Furthermore, t is the study period while ECT is the error correction term with its coefficient being $\varnothing$.

Results of the study

Unit root and cointegration tests results

The analysis began by testing for unit root in the variables. From the results displayed in Table 5, all the series had an $I(1)$ order of integration collaborating those of Li et al. (2020a, b) for some selected quoted entities in Ghana, Khan et al. (2019) for Pakistan, Musah et al. (2021d, 2022a, b) for Ghana and the G20, and Danish and Ulucak (2020) for China. The variables' integration order underscores the adoption of the ARDL, FMOLS and the DOLS techniques, since they are fitting for variables that exhibit first difference stationarity. The variables' order of integration also implies they could be related in the long-run. Therefore, the tests shown in Table 6 were undertaken to assess the cointegration properties of the variables. From the discoveries, the series were cointegrated in the long-term aligning those of Chen et al. (2022), Phale et al. (2021), Li et al. (2021) and Musah et al. (2020a, b, c). This implies proceeding to estimate the parameters of the predictors was well in line.

Model estimation and causality results

Having established cointegration association between the variables, the ARDL technique was first adopted to explore the elasticities of the covariates. Based on the estimates indicated in Table 7, EC spurred CO_2 emanations in China. *Ceteris paribus*, a 1% rise in EC surged CO_2 effusions by 6.227% and 4.[illegible]5% in both the long and the short run respectively. This means that the country's economic activities were linked to the utilization of polluting energies like coal and fossil fuel among other, which exacerbated the rate of emissions in the nation. Explorations by Abbasi and Adedoyin (2021) and Musah et al. (2021c) offer support to the study's finding, but those by Kirikkaleli and Adebayo (2021a, b) and Anwar et al. (2021) are conflicting to the above disclosure. Also, IND worsened environmental quality by 2.172% and 1.395% in both the long and the short run correspondingly. This revelation is not surprising in that China has witnessed a major economic expansion of late, thanks to the rise in the country's industrial activities. However, majority of the industries in the nation are highly reliant on carbon-intensive energies sources, which pollute the environment. Studies by Ullah et al. (2020) and Rehman et al. (2021a) align the outcome of the study, but those by Appiah et al. (2021) and Zhou and Li (2020) deviate from

Table 5 Unit root tests results

Variable	Levels			First difference		
	ADF	PP	Decision	ADF	PP	Decision
$lnCO_2$	77.293	125.855	$I(0)$	113.371	195.822	$I(1)$
	0.621	0.202		0.000***	0.000***	
lnEC	54.347	80.438	$I(0)$	108.602	254.807	$I(1)$
	0.538	0.318		0.021**	0.000***	
lnIND	91.012	140.146	$I(0)$	153.209	395.729	$I(1)$
	0.302	0.903		0.000***	0.000***	
lnTI	40.365	82.619	$I(0)$	66.385	266.498	$I(1)$
	0.943	0.111		0.061*	0.000***	
lnURB	89.532	198.388	$I(0)$	140.601	421.361	$I(1)$
	0.212	0.422		0.000***	0.000***	

The top values for the variables denote unit root statistics, while the down values represent probabilities. Also, ***, **, and * denote significance at the 1%, 5%, and the 10% levels respectively.

Table 6 Cointegration tests results

ARDL bound test results									
Statistic		10%		5%		1%		*p* value	
		I(0)	*I*(1)	*I*(0)	*I*(1)	*I*(0)	*I*(1)	*I*(0)	*I*(1)
F statistic	8.114	1.429	4.925	2.183	3.143	3.966	7.332	0.004	0.008
t statistic	−6.231	−4.534	−3.346	−5.196	−3.514	−4.344	−2.878	0.002	0.005
Johansen cointegration test results									
No. of CE(s)	Trace stat	Prob.**	Max. Eigen Stat	Prob.**					
None*	155.292	0.001	97.291	0.002					
At most 1*	88.101	0.003	50.143	0.005					
At most 2*	48.355	0.005	36.344	0.006					
At most 3*	25.817	0.007	117.217	0.008					
At most 4*	10.019	0.035	6.238	0.039					
At most 5*	0.734	0.044	0.436	0.048					

The ARDL bound test was supported by the Kripfganz and Schneider (2018) critical value bounds and approximate *p* values. Also, both the trace and the max-eigenvalue test indicate 6 cointegrating eqn(s) at the 0.05 level. Finally, * denotes rejection of the null hypothesis at the 0.05 level while ** represents the MacKinnon-Haug-Michelis (1999) *p* values.

the above discovery. Moreover, TI improved environmental quality in the country. Specifically, a 1% surge in TI mitigated CO_2 emissivities by 3.214% and 2.293% in the long and the short run respectively. This finding suggests that technology was key in the nation's strive towards a low-carbon economy. Empirical explorations by Chen and Lee (2020) and Yu and Du (2019) agree with the discovery of the study, but those by Khattak et al. (2020) and Villanthenkodath and Mahalik (2020) vary from the above disclosure.

Furthermore, URB worsened environmental quality in China. *Ceteris paribus*, a 1% change in URB escalated CO_2 effusions by 4.411% and 3.332% in both the long and the short run correspondingly. This result implies, URB led to developments in economic activities like industrialization and the creation of basic infrastructure like roads, bridges, and markets, which are heavily reliant on the utilization of polluting energies, leading to more effusions. Put simply, URB policies of the nation did not help to propel ecological welfare targets of the country. The discovery collaborates those of Solarin et al. (2017) and Ali et al. (2019), but deviates from those of Rafiq et al. (2016) and Azam and Khan (2016). Lastly, the ECT was substantially negative at the 1% level. The ECT value of − 0.716 implies the speed of adjustment towards the long-run equilibrium was 71.6%. The adjusted R^2 value of 0.805 signifies that 80.5% of the variations in CO_2 effluents were explained by the predictors, while the significant *F* value signposts that the model had a very high explanatory power. In order to check the validity of the model, the diagnostic tests indicated in Table 7 were undertaken. From the Breusch Godfrey LM test, there was no serial correlation in the residuals of the model. Also, ARCH and Breusch-Pagan-Godfrey tests found no homoscedastic in the error terms. Furthermore, the model was well specified based on the Ramsey RESET test. Finally, the residual terms were normally distributed as per the Jarque–Bera test results. For robustness purpose, the FMOLS and the DOLS estimates were finally explored. From the estimates displayed in Table 8, EC, IND, and URB

Table 7 ARDL estimation results

Variable	Coeff	SE	*t* statistic	Prob
$lnEC_{t-1}$	6.227	1.5151	[illegible]	0.005***
$\Delta ln\ EC_t$	4.145	1.2833	3.23	0.007***
$lnIND_{t-1}$	2.172	[illegible]	2.27	0.025**
$\Delta lnIND_t$	1.395	[illegible]	2.01	0.043**
$lnTI_{t-1}$	−3.214	[illegible]	−3.89	0.059*
$ln\Delta TI_t$	−2.293	1.1943	−1.92	0.028***
$lnURB_{t-1}$	4.411	2.0234	2.18	0.003***
$\Delta lnURB_t$	3.332	2.1497	1.55	0.007**
Constant	[illegible]	1.3526	3.88	0.001***
ECT_{t-1}	−0.716	0.2295	−3.12	0.004***
R^2	0.821	B-P-G test	0.821(0.556)	
Adjusted R^2	0.805	ARCH test	0.725(0.646)	
F statistic	116.334 (0.008)***	RESET test	0.641(0.477)	
B-G LM test	1.102(0.913)	J-B test	1.882(0.712)	

$lnCO_2$ the response variable, *SE* for standard errors, *B-G LM test* Breusch-Godfrey LM test, *B-P-G test* Breusch-Pagan-Godfrey test, *ARCH* signifies autoregressive conditional heteroscedastic test, *J-B* Jarque–Bera test, and *RESET test* Ramsey regression equation specification error test. Also, *, **, **, * denote significance at the 1%, 5%, and the 10% levels respectively, while values in parenthesis () represent probabilities.

Table 8 FMOLS and DOLS estimation results

FMOLS results				
Variable	Coefficient	Std. error	*t* statistic	Prob
lnEC	0.827	0.097	8.526	0.000***
lnIND	0.692	0.163	4.245	0.086*
lnTI	-0.017	0.008	-2.125	0.019**
lnURB	1.868	0.592	3.155	0.025**
R-squared	0.891			
Adjusted R-squared	0.802			
DOLS results				
Variable	Coefficient	Std. error	*t* statistic	Prob
lnEC	0.858	0.111	7.730	0.000***
lnIND	0.376	0.179	2.101	0.017**
lnTI	−0.912	0.209	−4.364	0.072*
lnURB	2.407	0.657	3.664	0.061*
R-squared	0.791			
Adjusted *R*-squared	0.719			

$lnCO_2$ response variable; and ***, **, and * denote significance at the 1%, 5%, and the 10% levels respectively.

worsened EQ by 0.827%, 0.692%, and 1.868% respectively. However, TI improved EQ by 0.017%. The weight of the coefficients and the levels of significance under the two estimators were dissimilar from the ARDL technique. However, the parameters of the predictors in terms of sign were the same under the three approaches. This underscores the robustness of the study's results. The elastic effects of the predictors on the response variable are illustrated in Fig. 1.

At the final stage, the VECM of Engle and Granger (1987) was engaged to explore the causality between the

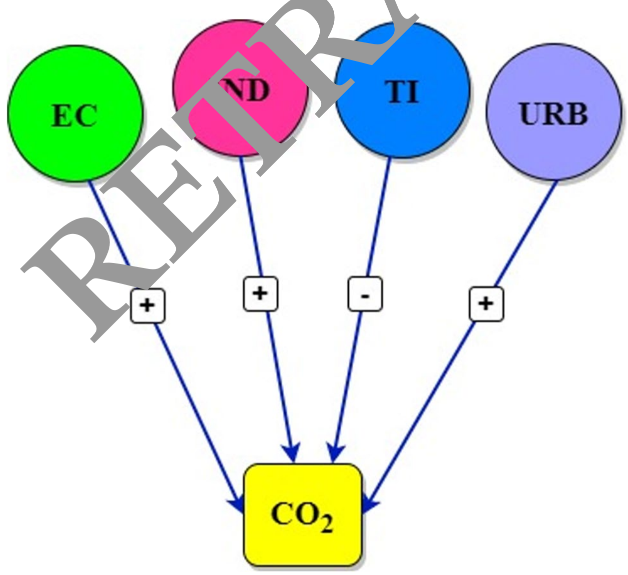

Fig. 1 The elastic effects of the predictors on the response variable

variables. Based on the estimates displayed in Table 9, a causation from EC to CO_2 effusions was unfolded. This implies carbon emissivities were reliant on energy consumption in the country. Studies by Musah et al. (2021a) and Li et al. (2020a) align the finding of the study, but those by Doğanlar et al. (2021) deviate from the above outcome. Also, IND and CO_2 emissions were mutually related. This means the two variables were dependent on each other. The rise in IND led to a rise in CO_2 effusions and vice versa. Empirical explorations by Liu and Bae (2018) and Al-Mulali and Ozturk (2015) support the above revelation, but that of Musah et al. (2021) contradicts the study's discovery. Moreover, there was no causality between TI and CO_2 emanations in the country. This signposts that the two series did not cause each other. Investigations by Bashir et al. (2020) and Abid et al. (2021) are in tandem with the above revelation, but that of Sana et al. (2021) varies from the study's finding. Finally, a double-headed causality between CO_2 effluents and URB was disclosed. This means, the two variables caused each other or were inter-dependent on each other. Implying a rise in one variable led to a rise in the other variable and vice versa. Studies by Ahmed et al. (2019) and Salahuddin et al. (20[illegible]) offer support to the study's outcome, but those by Haseeb et al. (2018) and Mesagan and Nwachukwu (2018) contrast the outcome of the study.

Conclusions and policy recommendations

This study examined the connection between energy utilization and environmental quality in China for the period 1971 to 2018. Robust econometric methods that offer valid and reliable results were used for that analysis. From the results, all the variables had *I*(1) order of integration and were flanked by a long-term cointegration association. The coefficients of the predictors were first explored via the ARDL estimator and from the discoveries, energy utilization degraded ecological quality in the country via high CO_2 effusions. Also, industrialization and urbanization deteriorated the country's environmental quality; however, technological innovations improved ecological quality in the nation. The FMOLS and the DOLS estimates were also explored to help check the vigorousness of the ARDL results, and from the revelations, the parameters of the predictors in terms of sign under the FMOLS and the DOLS techniques were the same as those under the ARDL approach. This suggests that the results were valid and reliable. The causal connections between the series were explored via the VECM of Engle and Granger (1987) and from the results, a unidirectional causality from energy consumption to CO_2 effluents was discovered. Also, feedback causalities between industrialization and CO_2 secretions, and between urbanization and CO_2 exudates were disclosed. However, there was no causality

Table 9 Pairwise Granger causality tests results

Variable	$lnCO_2$	lnEC	lnIND	lnTI	lnURB	ECT
$lnCO_2$	-	3.351	4.194	2.192	4.143	−0.772
		(0.147)	(0.003)***	(0.118)	(0.023)**	(0.001)***
lnEC	5.432	-	6.656	2.421	8.074	−0.662
	(0.004)***		(0.411)	(0.035)**	(0.078)*	(0.008)***
lnIND	4.412	0.261	-	1.318	0.193	−0.718
	(0.016)**	(0.044)**		(0.783)	(0.808)	(0.037)**
lnTI	6.174	2.138	1.361	-	1.621	−0.812
	(0.701)	(0.178)	(0.049)**		(0.2[illegible])	(0.007)***
lnURB	3.147	0.234	2.012	1.142		−0.792
	(0.053)*	(0.145)	(0.345)	(0.034)**		(0.048)**

$lnCO_2$ response variable, while values in parenthesis () represent probabilities. Finally, ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively.

between technological innovations and CO_2 emanations. The causal connections amidst the series are depicted in Fig. 2.

Based on the findings, the study concludes that energy consumption, industrialization, and urbanization are harmful to environmental quality in China, but technological innovations help to advance ecological quality in the country. With reference to the above conclusions, the study recommends that since energy consumption pollutes the environment, the country should transition to the utilization of renewable energies. Also, the government should allocate more resources to the renewable energy sector. This will help increase the portion of clean energy in the country's total energy mix. Furthermore, research and development that are linked to the utilization of green energies should be supported by the government. Moreover, majority of people are not aware of the environmental consequences of dirty energies and the health benefits of green energies. Therefore, the government should intensify its awareness creation strategies to help attain the aforestated issues. Since industrialization added to environmental pollution in the country, the Chinese government should ban the establishment of polluting industries in the country. However, industries that factor ecologically friendly issues in their operations should be permitted to operate in the country. Also, the government can reduce the tax burden of environmentally friendly industries, while increasing that of environmentally unfriendly ones. This will propel the latter to shift to ecologically friendly activities. From the discoveries, urbanization also degraded environmental quality in the country. As a recommendation, the Chinese government should improve the living standards of people in remote areas. This will prevent them from migrating to urban cities. Also, basic infrastructural facilities that attract people to move to urban centers should be provided for them in their respective localities. According to Behera and Dash (2017), sustainable urbanization model rather than unsustainable urbanization model should adopted in managing the rate of urbanization in economies. Therefore, following the above authors, sustainable urbanization model should be adopted to control the rate of urbanization in the country. Finally, because technological innovations helped to improve environmental quality in the country, the government should advocate for the adoption of environmentally friendly technologies in all organizations and institutions. Data constraints was the main limitation of this exploration. For instance, there was no data available for the proxy of environment quality (CO_2 emissions) after 2018. Also, data for energy consumption was not available from 1960 to1970 and after 2014. Therefore, using the explained variable as the determining factor, the period 1971 to 2018 was deemed

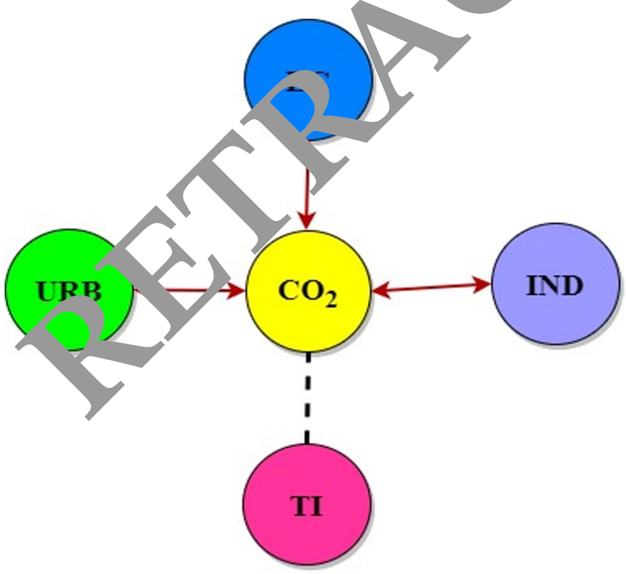

Fig. 2 The causal connections between the explained and the explanatory variables. Note: (↔) signifies a two-way causality between variables, (←) denotes a one-way causality between variables, and (--) represents no causality between variables

appropriate. This implies the data used for the analysis was not balanced. In future if the missing data become available, similar explorations could be conducted to check the robustness of the study's outcomes.

Author contribution KL conceptualized the study; HY drafted the original manuscript; YN helped in analysis and discussions; XW provided data; MM1 wrote the final manuscript; MM2 conducted the literature review and helped in analysis and discussions; MA helped in analysis and discussions; YC helped in analysis and discussions; HX helped in analysis and discussions; XY1 helped in analysis and discussions; XY2 helped in analysis and discussions; QJ helped in analysis and discussions; QH edited the final manuscript. All authors read and approved the final manuscript.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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