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Re-Estimating the Impact of Natural Gas on Global Carbon Emissions: The Role of Technological Innovation

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To investigate the nexus between natural gas consumption, global carbon dioxide (CO_2) emissions, and technological innovation, this study employs a balanced panel dataset of 73 countries for the period 1990–2019 based on the fixed effect and random effect estimation methods. Considering potential heterogeneity in the natural gas-CO_2 nexus, this study divides the 73 countries into regional comprehensive economic partnership (RCEP) countries and non-RCEP countries for comparative analysis. The main findings indicate that natural gas consumption can significantly promote CO_2 emissions for the full sample and non-RCEP countries, and improved technological innovation can help alleviate CO_2 emissions from natural gas consumption. In the RCEP countries, technological innovation can improve the carbon emission reduction effect of natural gas. Furthermore, economic growth and global CO_2 emissions show an inverted U-shaped relationship, which confirms the environmental Kuznets curve hypothesis. Finally, several policy implications are provided to reduce global CO_2 emissions and promote green recovery in the post-epidemic era.

Keywords: carbon emissions, natural gas consumption, technological innovation, RCEP and non-RCEP countries, global analysis

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INTRODUCTION

In recent years, the world has witnessed unparalleled economic growth. Simultaneously, this rapid growth has been accompanied by abundant energy consumption and global CO_2 emissions. According to statistics from BP (formerly British Petroleum) (BP, 2020), the world's total primary energy consumption increased nearly twofold between 1990 and 2019, from 7,820.7 million tons of oil equivalent (Mtoe) to 13,301.4 Mtoe, respectively. This rapidly increasing energy consumption has imposed tremendous environmental pressures on the world, particularly from the huge amount of carbon dioxide (CO_2) emissions released into the atmosphere (Dong et al., 2018a). Based on statistics from BP (2020), global CO_2 emissions have increased approximately 1.6 times in the past few decades from 21,331.5 million tons (Mt) in 1990 to 34,169.0 Mt in 2019. The increasing global CO_2 emissions and the associated global warming have ignited worldwide concerns. Thus, many scholars have focused on the factors driving global CO_2 emissions (Chebbi et al., 2011; Shahzad et al., 2017; Mahmood et al., 2019). In the meantime, a widely accepted pathway to alleviate the environmental pressure is to expand natural gas consumption, which is considered relatively cleaner, high-efficiency, and low-carbon transmit energy (Dong et al., 2019; Zhao et al., 2020a; Jiang et al., 2020). Accordingly, several scholars have studied the impact of natural gas consumption on CO_2 emissions (Peters et al., 2011; Dong et al., 2017; Dong et al., 2018b). For example, Jiang et al. (2021) propose that natural gas can significantly reduce carbon abatement cost and thus curb CO_2 emissions. Moreover, with rapid advances in technology, many scholars have recognized the environmentally friendly effect of technological innovation. However, to the best of our knowledge, most studies on the relationship between natural gas consumption and CO_2 emissions are based on a national or regional level, and very few researches have investigated the natural gas-CO_2 nexus from a global perspective. Furthermore, prior literature has often examined the impacts of natural gas consumption and technological innovation on CO_2 emissions respectively. For example, some scholars investigate the impact of natural gas consumption on CO_2 emissions, but not considering the effect of technological innovation in the nexus (Alkhathlan and Javid, 2013; Saboori and Sulaiman, 2013; Dong et al., 2018d). In addition, there are some studies that only focus on the nexus between technological innovation on CO_2 emissions which ignore the impact of natural gas consumption on CO_2 emissions (York et al., 2003; Irandoust, 2016; Yii and Geetha, 2017). However, to the best of our knowledge, very few studies have systematically investigated the nexus between natural gas consumption, CO_2 emission, and technological innovation under a unified framework.

Furthermore, with rapid globalization, countries around the world are becoming more closely linked, in both international trade and environmental governance. Recently, on November 15, 2020, 15 member countries covering the ten Association of Southeast Asian Nations (ASEAN) countries and China, Japan, South Korea, Australia, and New Zealand formally signed the Regional Comprehensive Economic Partnership (RCEP) agreement, thus forming the world's largest Free Trade Agreement (FTA). The agreement covers the largest participating population in the world, the most diverse membership structure, and the largest development potential. The signing of the RCEP will not only reshape the rules of economics and trade in the Asia-Pacific region, but will also have spillover effects on the construction of a new energy system in the Asia-Pacific region. For example, Japan and South Korea have relatively higher energy efficiency and more advanced technological innovation due to their higher levels of natural gas consumption and energy dependence. Thus, the technology spillover effect among the countries which sign the RCEP agreement might be stronger. Furthermore, most RCEP countries have relatively higher environmental regulations, which might influence the development of domestic natural gas market reforms and air pollution. These factors might cause a structural shock in the nexus between natural gas consumption, CO_2 emissions, and technological innovation. However, the existing literature that further discuss the regional heterogeneity mainly focuses on the income level of countries or geographical positions. For example, Dong et al. (2020a) investigate the relationship between renewable energy consumption and global CO_2 emissions based on countries with different income levels. Thus, to the best of our knowledge, few studies have investigated the potential heterogeneity in the nexus between natural gas, CO_2 emissions, and technological innovation between the RCEP countries and non-RCEP countries.

To fill the academic gaps discussed above, this study first investigates the impact of natural gas consumption on global CO_2 emissions by employing a balanced panel dataset for 73 countries covering the period 1990–2019. Then we systematically conduct an empirical analysis of the role of technological innovation in natural gas-CO_2 emissions. Furthermore, to detect whether heterogeneity exists in the nexus between natural gas consumption, CO_2 emissions, and technological innovation, this study divides the full panel data into two subsamples, the RCEP countries and the non-RCEP countries, and conducts a comparative analysis based on the fixed effect (FE) and random effect (RE) estimation methods. Accordingly, this study contributes to the existing literature in the following three aspects: 1) This study systematically investigates the nexus between natural gas consumption, global CO_2 emissions, and technological innovation by putting the three factors into a unified framework. On the one hand, the impact of the natural gas consumption and technological innovation on global CO_2 emissions are investigated from the respective coefficient in the empirical framework; on the other hand, the cross impact of the technological innovation and natural gas consumption is examined. The estimation results are not only conducive to better understanding the impact of natural gas consumption and technological innovation on CO_2 emissions, but are also beneficial for policymakers to formulate precise policies to mitigate environmental degradation; 2) this study divides the full panel into two groups (i.e., the RCEP countries and the non-RCEP countries) for a heterogeneous analysis by conducting Dumitrescu-Hurlin (D-H) panel causality test among the two different subsamples. The results provide new evidence for policymakers to implement specific policies that are conducive to carbon reduction; and 3) this study also examines the environmental Kuznets curve (EKC) hypothesis by introducing the quadratic term of economic growth into the empirical model, and the estimation results provide a reference for policymakers to formulate policies that promote green recovery in the post-epidemic era.

The remainder of this study is organized as follows. *Literature Review and Research Gap* presents the existing relevant literature. *Empirical Model and Data* presents the empirical model and data. *Estimation Strategy* provides the estimation strategy. *Empirical Results* reports the empirical estimation results. *Conclusion and Policy Implications* concludes this study and provides some implications.

LITERATURE REVIEW AND RESEARCH GAP

Studies on the Natural Gas-CO_2 Nexus

In recent years, a growing body of scholars has focused on the relationship between natural gas and CO_2 emissions. For instance, Lotfalipour et al. (2010) explore the causal relationship between natural gas consumption and carbon emissions in Iran and find a unidirectional causality running from natural gas consumption to CO_2 emissions. Similar results are reported by Pereira and Pereira (2010), who investigate the nexus of natural gas consumption and CO_2 emissions in Portugal. However, some researchers, such as Alkhathlan and Javid (2013) for Saudi Arabia, Dong et al. (2018d) for 14 Asia-Pacific countries, and Saboori and Sulaiman (2013) for Malaysia, uncover a bidirectional causality between natural gas consumption and CO_2 emissions. Furthermore, Shearer et al. (2014) investigate the impact of natural gas consumption on CO_2 emissions in the United States, and find that increased natural gas consumption could induce more CO_2 emissions and thus delay the process of decarbonization. They also claim that the promoting effect of natural gas consumption on CO_2 emissions is attributed to it delaying deployment of renewable energy technologies. However, some other researchers obtain the opposite conclusion, which indicates natural gas can reduce CO_2 emissions. For example, based on the data for China for the period 1965–2016, Dong et al. (2018b) find a significant mitigating effect of natural gas consumption on CO_2 emissions. They insist that natural gas is a relatively cleaner transmit fuel, which can curb CO_2 emissions effectively. However, they also propose that in the long run, the mitigation effect of CO_2 emissions will shrink because it is composed primarily of methane which would produce substantial CO_2 emissions. Their findings are confirmed by Dong et al. (2017) for BRIC countries, Su et al. (2017) for Singapore, and Xie (2014) for China. Thus, to date, the relationship between natural gas consumption and CO_2 emissions is still controversial among scholars.

Studies on the Technological Innovation-CO_2 Nexus

The impact of technological innovation on CO_2 emissions has attracted the attention of numerous researchers in the past few decades. Most scholars believe technological innovation is conducive to reducing CO_2 emissions. For example, by using the VECM and TYDL granger causality tests, Yii and Geetha (2017) find a negative correlation between technological innovation and CO_2 emissions. Based on the STIRPAT model, York et al. (2003) have explored the influencing factors of CO_2 emissions and conclude that technological innovation can significantly reduce CO_2 emissions. Their results are consistent with Irandoust (2016), Zhao et al. (2010), and Zhao et al. (2013), who investigate the relationship between technological innovation and CO_2 emissions based on the LMDI, ARDL, and VAR models, respectively. However, Wang et al. (2017a) propose that the impact of technological innovation on CO_2 emissions varies according to different levels of economic development. Specifically, technological innovation could reduce CO_2 emissions under high economic development but increase CO_2 emissions under low economic development. Their findings are supported by Chen and Lee (2020) for 96 countries and Cheng et al. (2019) for OECD countries. Based on the literature review above, the existing studies on the relationship between technological innovation and CO_2 emissions are mainly based on time series data, which cannot capture the individual effect information among countries. Thus, in this study, we employ the commonly used estimation methods, (i.e. FE and RE) that are appropriate for panel data to investigate the impact of technological innovation on global CO_2 emissions.

Studies on the Determinants of CO_2 Emissions

In addition to the above factors, (i.e. natural gas consumption and technological innovation), some other variables are frequently presented as influencing factors on CO_2 emissions. These factors include mainly economic growth, industrial structure upgrading, population, trade openness, and urbanization level. Specifically, many scholars have widely investigated the EKC hypothesis proposed by Grossman and Krueger (1993) (Iwata et al., 2012; Baek, 2015; Bilgili et al., 2016; Zhang et al., 2017; Dong et al., 2018c). This hypothesis depicts an inverted U-shaped relationship between economic growth and CO_2 emissions. Specifically, according to the EKC hypothesis, further economic growth can improve environmental degradation after an economy has reached an adequate level of economic growth (Kaika and Zervas, 2013). As for industrial structure upgrading, it has been verified that industrial structure upgrading is a significant driving factor of CO_2 emissions (Li et al., 2017; Chen et al., 2019; Tian et al., 2019), and most studies indicate that industrial structure upgrading can reduce CO_2 emissions significantly. In terms of population, Dong et al. (2018a) and Li et al. (2017) propose that population can significantly contribute to CO_2 emissions, a proposition supported by Dong et al. (2020b), Ghazali and Ali (2019), and Wang et al. (2019). In contrast, Wang et al. (2017b) oppose the above arguments and reveal a negative correlation between population size and CO_2 emissions. Furthermore, many researchers have examined the impact of trade openness on CO_2 emissions. For example, Ahmed et al. (2017), Ansari et al. (2020), and Bernard and Mandal (2016) find that trade openness has a positive impact on CO_2 emissions. However, based on a dataset for OECD countries covering the period 1960–2013, Gozgor (2017) reveals that trade openness affects CO_2 emissions negatively in the long run. This mitigation effect is evident in many other studies such as that by Ho and Iyke (2019) for central and eastern European countries and that by Lv and Xu (2019) for middle-income countries. Many other scholars have also attested to the significant impact of urbanization level on CO_2 emissions (Martínez-Zarzoso and Maruotti, 2011; Zhang and Lin, 2012; Sadorsky, 2014; Shahbaz et al., 2016; Liu and Bae, 2018). Additionally, some other factors are considered to be the driving forces of CO_2 emissions, such as foreign direct investment (FDI) (Omri et al., 2014; Bakhsh et al., 2017; Haug and Ucal, 2019), industrialization (Li and Lin, 2015; Xu and Lin, 2015; Liu and Bae, 2018), and lifestyle change (Wei et al., 2007; Feng et al., 2009; Li et al., 2019). Notably, these factors are not taken into the empirical model in this study.

The preceding studies have investigated the impact of natural gas consumption on CO_2 emissions. However, certain research gaps still exist. First, most studies over the natural gas-CO_2 emissions nexus are based on the national or regional level.

To the best of our knowledge, very few researches have systematically investigated the relationship between natural gas consumption and CO_2 emissions from a global perspective, which could provide more generalized evidence for policymakers to formulate appropriate policies to reduce CO_2 emissions. Second, the existing literature often ignores heterogeneity in the natural gas-CO_2 emissions nexus. Based on the literature review, the studies that consider the heterogeneity in the nexus between natural gas consumption and CO_2 emissions mainly focus on the income levels or the geographical positions of countries. However, very few studies have investigated the difference in the impact of natural gas consumption on CO_2 emissions between the RCEP countries and the non-RCEP countries. Third, it is evident that most studies over the nexus between natural gas consumption, technological innovation, and CO_2 emissions investigate the impact of natural gas consumption and technological innovation on CO_2 emissions respectively. And to the best of our knowledge, very few studies have examined the nexus between the three variables in a unified framework. Furthermore, few scholars have explored the impact of technological innovation on the natural gas-CO_2 emissions nexus, which is not conducive to clearly analyzing the causal relationships between natural gas consumption, CO_2 emissions, and technological innovation.

EMPIRICAL MODEL AND DATA

Estimation Model

To empirically explore the causal natural gas-CO_2 nexus, this study examines the impact of natural gas consumption and technological innovation on global CO_2 emissions based on the static panel model. Based on the conventional STIRPAT model reformulated by Dietz and Rosa (1997), we construct an econometric model as follows: CO_2 emissions are utilized as the dependent variable, while natural gas consumption and technological innovation are used as the main independent variables. Following the discussion in *Studies on the Determinants of CO_2 Emissions*, this study further introduces economic growth, industrial structure upgrading, trade openness, population, and urbanization level as control variables. Furthermore, to verify the EKC hypothesis of global CO_2 emissions, this study also introduces the square term of economic growth. The multivariate framework is presented as follows:

$$CO_{2it} = f\left(NGC_{it}, Tec_{it}, Pgdp_{it}, Pgdp_{it}^2, Ind_{it}, Pop_{it}, Tra_{it}, Urb_{it}\right), \tag{1}$$

where subscripts i and t represent the country and year, respectively. CO_2 indicates the CO_2 emissions of various countries, NGC denotes natural gas consumption, Tec refers to technological innovation, $Pgdp$ means economic growth, Ind represents industrial structure upgrading, Pop indicates the population of each country, Tra refers to trade openness, and Urb represents the urbanization level.

To eliminate the effect of variable dimension as well as the potential heteroscedasticity problem of the data series, this study takes the natural logarithm of all variables in **Eq. 1**, which is shown as follows:

$$LnCO_{2it} = \alpha_0 + \alpha_1 LnNGC_{it} + \alpha_2 LnTec_{it} + \sum_{k=3}^{8} \alpha_k LnX_{it} + \varepsilon_{it}, \tag{2}$$

where α_0 and ε_{it} represent the intercept and random disturbance terms, respectively. $\alpha_1 - \alpha_8$ are the parameters to be estimated. X indicates a vector including a series of control variables, i.e., economic growth, industrial structure upgrading, trade openness, population, and urbanization level.

In addition, to systematically explore the influence of technological innovation on the impact of natural gas consumption in global CO_2 emissions, we further introduce the interaction term of technological innovation and natural gas consumption on the basis of **Eq. 2**; thus, **Eq. 2** can be rewritten as follows:

$$LnCO_{2it} = \beta_0 + \beta_1 LnNGC_{it} + \beta_2 LnTec_{it} + \beta_3 LnNGC{*}LnTec + \sum_{k=4}^{9} \beta_k LnX_{it} + \varepsilon_{it}, \tag{3}$$

where β_0 and ε_{it} indicate the intercept and random disturbance terms, respectively. $\beta_1 - \beta_9$ refer to the estimated parameters.

Variable Measurements and Data Sources

In this study, a balanced panel dataset covering 73 countries for the period 1990–2019 is utilized to investigate the impact of natural gas consumption and technological innovation on global CO_2 emissions, yielding a total of 2,190 observations. Notably, due to data limitations, other countries are not considered. Furthermore, with the signing of the RCEP, the world's largest free trade agreement, it is important to explore the differences in the impact of natural gas consumption and technological innovation on CO_2 emissions between RCEP and non-RCEP countries. Thus, the 73 countries are divided into RCEP countries (12 countries) and non-RCEP countries (61 countries); the specific countries are highlighted in **Table A1** in the Appendix.

The data on CO_2 emissions (denoted as CO_2) and natural gas consumption (denoted as NGC) of each country are obtained from the BP Statistical Review of World Energy (BP, 2020). Technological innovation (denoted as Tec) is measured by the ratio of GDP to energy consumption, where the data on energy consumption are from BP (2020), while the data on GDP are obtained from the World Bank. (2020). Economic growth (denoted as $Pgdp$) is measured by per capita GDP, industrial structure upgrading (denoted as Ind) is measured by the ratio of the added value of tertiary industry to secondary industry, population (denoted as Pop) is measured by the population of each country, trade openness (denoted as Tra) is measured by the ratio of total import and export trade to GDP; that is, trade dependence; and urbanization level (denoted as Urb) is measured by the proportion of the urban population to total population. The data on economic growth, industrial structure upgrading, population, trade openness, and urbanization level are collected

TABLE 1 | Description of all the selected variables.

Variable	Definition	Data source
CO_2	Carbon dioxide (CO_2) emissions	BP. (2020)
NGC	Natural gas consumption	BP. (2020)
Tec	Technological innovation	BP. (2020); World Bank. (2020)
Pgdp	Per capita gross domestic product (GDP)	World Bank. (2020)
Ind	The ratio of the added value of tertiary industry to the secondary industry	World Bank. (2020)
Tra	Trade openness	World Bank. (2020)
Pop	Population	World Bank. (2020)
Urb	Urbanization level	World Bank. (2020)

TABLE 2 | Descriptive statistics of all the selected variables (after logarithm).

Panel	Variables	Obs.	Mean	Std. dev.	Min	Max
Global panel	$LnCO_2$	2190	4.711829	1.383155	1.938211	9.192767
	LnNGC	2190	2.227654	1.92567	−5.279103	6.741282
	LnPgdp	2190	9.355232	1.254396	6.018994	11.62597
	$LnPgdp^2$	2190	89.09316	22.92353	36.22828	135.1632
	LnTec	2190	−1.692787	0.481996	−3.646372	−0.481987
	LnInd	2190	0.5621893	0.5177519	−2.082297	2.007518
	LnTra	2190	4.238189	0.6477828	−3.863269	6.080681
	LnPop	2190	16.79474	1.563094	12.85278	21.0581
	LnUrb	2190	4.18656	0.3017793	2.986237	4.60517
RCEP countries	$LnCO_2$	360	5.652064	1.430734	2.858019	9.192767
	LnNGC	360	2.572637	1.931899	−5.279103	5.727934
	LnPgdp	360	8.885996	1.462949	6.071393	10.98654
	$LnPgdp^2$	360	81.0952	25.91471	36.86182	120.704
	LnTec	360	−1.70509	0.3221202	−3.053031	−0.815232
	LnInd	360	0.4523649	0.3778658	−0.3387244	1.178982
	LnTra	360	4.264086	0.7599114	2.741244	6.080681
	LnPop	360	18.01789	1.748463	14.92971	21.0581
	LnUrb	360	4.009742	0.4578219	3.0085	4.60517
Non-RCEP countries	$LnCO_2$	1830	4.555271	1.306878	1.938211	8.680018
	LnNGC	1830	2.178944	1.923221	−4.855942	6.741282
	LnPgdp	1830	9.448844	1.189417	6.018994	11.62597
	$LnPgdp^2$	1830	90.6946	21.98763	36.22828	135.1632
	LnTec	1830	−1.697604	0.5064509	−3.646372	−0.4831987
	LnInd	1830	0.5859982	0.5396149	−2.082297	2.007518
	LnTra	1830	4.220192	0.6262307	−3.863269	6.012154
	LnPop	1830	16.5691	1.402305	12.85278	19.60925
	LnUrb	1830	4.227218	0.2468679	2.986237	4.60517

Notes: Std. dev., Min, and Max denote standard deviation, minimum, and maximum, respectively.

from the World Bank. (2020). The description of the variables is presented in **Table 1**, while the descriptive statistics (i.e., mean value, standard deviation, maximum value, and minimum value) of all the selected variables are shown in **Table 2**.

ESTIMATION STRATEGY

Technically, the estimation strategies in this study consist mainly of four steps: 1) Both the Breusch-Pagan Lagrange multiplier (LM) test and Pesaran cross-section dependence (CD) test are utilized to examine cross-sectional dependence within the panel data (see *Cross-Sectional Dependence Tests*); 2) the Pesaran cross-sectionally augmented Dickey-Fuller (CADF) and cross-sectionally augmented Im, Pesaran, and Shin (CIPS) panel unit root tests are utilized to examine the stationarity of each variable (see *Panel CADF and CIPS Unit Root Tests*); 3) the impacts of natural gas consumption and technological innovation on global CO_2 emissions are investigated by employing the FE and RE estimation methods simultaneously (see *FE and RE Estimates*); and 4) the causal nexus between the three main variables is explored by the Dumitrescu-Hurlin (D-H) panel causality test (see *Dumitrescu–Hurlin Panel Causality Test*).

Cross-Sectional Dependence Tests

To the best of our knowledge, the panel data used in this study may have the problem of potential cross-sectional dependence, which can cause inconsistent and invalid estimates (Grossman and Krueger, 1995; Zhao et al., 2020b). Moreover, in the current era of economic integration, complete independence is almost impossible. To effectively achieve the targeted objectives, this study first conducts cross-sectional dependence tests within the panel data.

The three most commonly used cross-sectional dependence test methods include the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test. By comparing the advantages and disadvantages of these three methods, this study employs the Breusch-Pagan LM test and the Pesaran CD developed by Breusch and Pagan (1980) and Pesaran (2004), respectively, to conduct cross-sectional dependence tests; the specific statistics are expressed in **Eqs 4Eqs 5**, respectively.

$$\text{LM} = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T_{ij}\hat{\rho}_{ij}^{2} \rightarrow \chi^2 \frac{N(N-1)}{2}, \tag{4}$$

$$CD_{\text{Pesaran (2004)}} = \sqrt{\frac{2}{i(i-1)}}\sum_{k=1}^{i-1}\sum_{j=k+1}^{i} T_{k,j}\rho_{\widehat{k,j}} \sim N(0,1). \tag{5}$$

Notably, the two stochastic variables described above are distributed as standard normal under the null hypothesis when $T_{ij} \rightarrow \infty$ and $N \rightarrow \infty$ as well.

Panel CADF and CIPS Unit Root Tests

Following the previous discussion, this study employs an updated panel unit root test that incorporates cross-sectional dependence. Notably, the first-generation panel unit root test is invalid when cross-sectional dependence exists within the panel data. Accordingly, this study selects the Pesaran CIPS test proposed by Pesaran (2007) for the panel stationarity test. The test statistic for the Pesaran CIPS is presented as follows:

$$\Delta Y_{it} = \gamma_i + \alpha_i Y_{i,t-1} + \beta_i \overline{Y}_{t-1} + \sum_{l=0}^{P}\gamma_{il}\Delta\overline{Y}_{t-l} + \sum_{l=1}^{P}\gamma_{il}\Delta Y_{i,t-l} + \varepsilon_{it}, \tag{6}$$

where $\overline{Y}_{t-l}$ and $\Delta\overline{Y}_{t-l}$ indicate the cross-sectional averages of lagged levels and first differences of individual series, respectively. From the cross-sectional augmented Dickey-Fuller (CADF), the CIPS test statistics are obtained as follows:

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{n}\text{CADF}_i. \tag{7}$$

Here, $CADF_i$ is the t-statistics in the CADF regression defined by **Eq. 7**.

FE and RE Estimates

Considering the potential existence of cross-sectional dependence in the panel data, this study employs the FE and RE estimation methods. Moreover, the FE and RE estimation methods could avoid the problem of omitted variables by controlling the individual effect in the panel data. Specifically, the FE model is appropriate for the conditions under which the individual factors are correlated with certain independent variables, while the RE model applies to the situation where the individual factors are unrelated to all the independent variables. Furthermore, to distinguish which estimation method is suitable for the panel data, the specification test principle proposed by Hausman (1978), namely the Hausman test, is utilized in this study. According to Baltagi (2006), when analyzing an empirical model using panel data, Hausman test is a usual and effective tool to select appropriate estimation method. This viewpoint is shared by many other scholars (Baltagi et al., 2003; Frondel and Vance, 2010; Amini et al., 2012). Thus, employing the Hausman test for model specification is valid in this study. And the null hypothesis of the Hausman test is non-correlation between individual factors and the independent variables, which indicates the RE estimation is more effective for the panel data. Additionally, to examine whether heterogeneity exists in the impact of natural gas consumption on CO_2 emissions, this study further divides the full sample into two subsamples, the RCEP countries and the non-RCEP countries, and makes a comparative analysis by estimating the natural gas-CO_2 emissions nexus in the two subsamples, respectively.

TABLE 3 | Results of the cross-sectional dependence tests.

Panel	Breusch–Pagan LM test	Pesaran CD test
Global panel	22556.29***	7.023***
RCEP countries	21062.07***	6.355***
Non-RCEP countries	20345.16***	5.646***

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

Dumitrescu–Hurlin Panel Causality Test

Exploring the causality direction between natural gas consumption, technological innovation, and CO_2 emissions is particularly useful for policymakers to formulate specific policies. Considering cross-sectional dependence, this study employs the D-H panel causality test proposed by Dumitrescu and Hurlin (2012) to investigate the causal nexus between the variables. This test can be conducted irrespective of $T > N$ or $N > T$ and also deals with heterogeneity in the slope coefficients and cross-sectional dependence (Khan et al., 2020).

EMPIRICAL RESULTS

Results of Cross-Sectional Dependence Tests

The results of the cross-sectional dependence tests for the full panel data and the two subsamples are all reported in **Table 3**. From the table, the statistics for both the Breusch-Pagan LM tests and the Pesaran CD tests are all higher than the critical values at the 1% significance level, which means the null hypotheses, (i.e. no cross-sectional dependence) are all rejected for the full panel and the groups of RCEP and non-RCEP countries. Accordingly, the existence of cross-sectional dependence is valid and should be considered in the following estimation procedures.

Results of the Panel CADF and CIPS Unit Root Tests

Considering the existence of cross-sectional dependence in the full panel and the two subsamples, the panel CADF and CIPS unit

TABLE 4 | Results of the panel CADF and CIPS unit root tests.

Panel	Variables	Pesaran CADF test		Pesaran CIPS test	
		Level	1st difference	Level	1st difference
Global panel	$LnCO_2$	−2.249	−3.767***	−2.234	−2.358***
	LnNGC	−2.558**	−3.958***	−2.505	−5.080***
	LnPgdp	−2.496**	−3.223***	−2.511	−3.894***
	$LnPgdp^2$	−2.398	−3.171***	−2.395	−3.856***
	LnTec	−2.232	−4.034***	−2.554	−5.265***
	LnInd	−2.354	−3.803***	−2.221	−4.864***
	LnTra	−3.197***	−4.215***	−2.657**	−4.761***
	LnPop	−2.701***	−3.977***	−2.037	−3.313***
	LnUrb	−2.346	−2.658***	−2.210	−2.845***
RCEP countries	$LnCO_2$	−2.234	−3.041***	−2.016	−4.511***
	LnNGC	−2.243	−4.144***	−2.298	−4.704***
	LnPgdp	−1.580	−3.494***	−1.677	−4.408***
	$LnPgdp^2$	−1.575	−3.475***	−1.858	−4.292***
	LnTec	−2.234	−3.175***	−2.019	−4.328***
	LnInd	−2.377	−3.384***	−2.495	−4.996***
	LnTra	−2.058	−3.236***	−2.267	−4.522***
	LnPop	−3.487***	−4.656***	−2.421	−2.786**
	LnUrb	−1.068	−3.605***	−0.771	−2.812**
Non-RCEP countries	$LnCO_2$	−2.302	−3.879***	−2.220	−5.280***
	LnNGC	−2.404	−3.926***	−2.421	−5.154***
	LnPgdp	−2.535**	−3.215***	−2.609	−3.869***
	$LnPgdp^2$	−2.466*	−3.166***	−2.494	−3.815***
	LnTec	−2.321	−4.189***	−2.636*	−5.433***
	LnInd	−2.361	−3.922***	−2.275	−4.870***
	LnTra	−3.297***	−4.275***	−2.676**	−4.838***
	LnPop	−3.016***	−3.870***	−2.141	−3.281***
	LnUrb	−2.252	−2.656***	−2.465	−4.390***

*Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Optimal lag lengths were selected automatically using the Schwarz information criteria.*

TABLE 5 | Results of the FE and RE estimates for the full sample.

Variables	FE estimation		RE estimation	
	(1)	(2)	(3)	(4)
LnNGC	0.025***	0.009	0.029***	0.012
	(6.92)	(0.96)	(8.13)	(1.22)
LnTec	−0.980***	−0.955***	−0.945***	−0.919***
	(−54.35)	(−41.32)	(−54.61)	(−40.92)
LnNGC*LnTec		−0.010*		−0.011*
		(−1.73)		(−1.89)
LnPgdp	1.862***	1.859***	1.878***	1.875***
	(24.70)	(24.67)	(24.88)	(24.86)
$LnPgdp^2$	−0.054***	−0.054***	−0.057***	−0.057***
	(−13.11)	(−13.15)	(−14.03)	(−14.06)
LnInd	−0.059***	−0.058***	−0.065***	−0.063***
	(−5.69)	(−5.53)	(−6.19)	(−6.00)
LnTra	−0.026***	−0.027***	−0.023***	−0.025***
	(−4.20)	(−4.40)	(−3.69)	(−3.91)
LnPop	1.021***	1.021***	1.015***	1.014***
	(61.35)	(61.36)	(71.15)	(71.00)
LnUrb	0.277***	0.290***	0.281***	0.295***
	(5.61)	(5.81)	(5.81)	(6.04)
_Cons	−27.798***	−27.769***	−27.521***	−27.487***
	(−69.29)	(−69.19)	(−70.97)	(−70.81)
Hausman test	0.0000			
Obs.	2190	2190	2190	2190
R^2	0.9040	0.9048	0.9133	0.9137

*Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent z-statistics.*

root tests are utilized to examine the stability of the relevant series; the results are listed in **Table 4**. As the table shows, for the global panel sample, the series data are not all stable at the level, whereas the first-differentiated variables are all stable due to the significant statistics of the two panel unit root tests. This indicates that the selected variables in the global panel are integrated of order, [i.e. I (1)], which ensures stable estimations of the empirical model. Similarly, with respect to the data for RCEP countries, all the selected variables are all integrated of order and thus valid for model construction and empirical analysis. The same test results are evident for the variables of the non-RCEP countries. To conclude, the linear empirical model is valid in the full panel and the two subsamples, respectively, due to the same order of integration of the selected variables in all samples.

Results of the Natural Gas-CO_2 Nexus

Estimates for the Global Panel

Following the discussions above, this study estimates the natural gas-CO_2 nexus for the global panel, and the results are displayed in **Table 5**. Furthermore, to explore the impact of technological innovation on the natural gas-CO_2 nexus, we also re-estimate the empirical model by introducing the cross term of natural gas consumption and technological innovation into the empirical framework. The results of the FE and RE estimations are listed in the second and fourth columns, respectively. Also, the results of the Hausman tests are reported in the table. The *p*-value of the Hausman test statistic indicates that the null hypothesis, (i.e. no correlation between the individual effect and independent variables) is rejected. Thus, the FE estimates are considered as the benchmark results of the empirical model for the global panel. Notably, the results of the RE estimates are basically consistent with those of the FE estimates, which imply that the estimation results for the global panel are robust and reliable.

As for the natural gas-CO_2 nexus, it is evident that to date, natural gas consumption has a significant positive impact on global CO_2 emissions. Although natural gas is relatively cleaner transition energy, compared with other traditional energy, its utilization is still accompanied by increasing CO_2 emissions. Thus, increased natural gas consumption is not conducive to carbon reduction. However, when the impact of technological innovation on natural gas-CO_2 emissions is considered, that is, the cross term of natural gas consumption and technological innovation is introduced into the empirical model, the positive impact of natural gas consumption on CO_2 emissions is no more significant. This means the implementation of technological innovation can offset the negative effect of natural gas consumption on CO_2 emissions to some extent. Furthermore, the negative value of the coefficient of the cross term implies that the promoting effect of natural gas consumption on CO_2 emission would decline as technological innovation is developed. This might be because that when technological innovation is advanced, the utilization efficiency of natural gas consumption will improve, which will greatly reduce the amount of total energy use keeping other production activities constant. Furthermore, technological innovation could optimize the

TABLE 6 | Results of the FE and RE estimates across the RCEP and non-RCEP countries.

Variables	RCEP countries				Non-RCEP countries			
	FE estimation		RE estimation		FE estimation		RE estimation	
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
LnNGC	0.007	–0.117**	0.022***	–0.073	0.015***	0.001	0.021***	0.006
	(1.05)	(–2.32)	(3.17)	(–1.30)	(3.36)	(0.08)	(4.83)	(0.57)
LnTec	–0.578***	–0.363***	–0.519***	–0.384***	–1.022***	–0.999***	–0.982***	–0.959***
	(–10.47)	(–3.53)	(–9.28)	(–3.70)	(–53.67)	(–41.86)	(–54.17)	(–41.50)
LnNGC*LnTec		–0.072**		–0.060*		–0.009		–0.010*
		(–2.48)		(–1.84)		(–1.55)		(–1.68)
LnPgdp	1.712***	1.629***	1.429***	1.083***	1.826***	1.836***	1.841***	1.852***
	(11.96)	(11.17)	(9.58)	(6.18)	(20.88)	(20.94)	(21.05)	(21.13)
LnPgdp^2	–0.057***	–0.056***	–0.036***	–0.019**	–0.051***	–0.052***	–0.054***	–0.055***
	(–7.01)	(–6.96)	(–4.42)	(–2.05)	(–10.65)	(–10.76)	(–11.46)	(–11.57)
LnInd	–0.286***	–0.222***	–0.276***	–0.161**	–0.056***	–0.055***	–0.061***	–0.060***
	(–4.65)	(–3.36)	(–4.19)	(–2.14)	(–5.46)	(–5.35)	(–5.95)	(–5.81)
LnTra	0.084***	0.087***	0.101***	0.232***	–0.023***	–0.024***	–0.021***	–0.023***
	(3.25)	(3.39)	(3.77)	(8.37)	(–3.65)	(–3.82)	(–3.45)	(–3.64)
LnPop	1.632***	1.665***	1.146***	1.068***	0.999***	0.997***	0.994***	0.991***
	(20.93)	(21.20)	(30.96)	(52.01)	(58.69)	(58.37)	(64.68)	(64.19)
LnUrb	0.260***	0.357***	0.305***	0.361***	0.313***	0.334***	0.280***	0.302***
	(2.97)	(3.74)	(3.27)	(3.41)	(4.83)	(5.05)	(4.47)	(4.72)
_Cons	–36.649***	–36.641***	–27.272***	–24.762***	–27.611***	–27.643***	–27.148***	–27.189***
	(23.07)	(–23.24)	(–29.40)	(3.41)	(–60.41)	(–60.44)	(–59.91)	(–59.97)
Hausman test	0.0000		0.0328					
Obs.	360	360	360	360	1830	1830	1830	1830
R^2	0.9499	0.9508	0.9440	0.9358	0.8717	0.8719	0.8712	0.8714

*Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent z-statistics.*

process of natural gas use, thus promoting cleaner production and mitigating CO_2 emissions.

As for the control variables, the coefficients of the control variables are all statistically significant, and their signs are basically in line with the actual conditions. Specifically, technological innovation can significantly reduce global CO_2 emissions. This is rational because the progress of technological innovation can improve energy efficiency and thereby reduce energy use while maintaining the current production level. Furthermore, an advance in technological innovation is conducive to promoting other alternative clean energy, which is conducive to environmental improvement. Moreover, the positive coefficient of economic growth and the negative coefficient of its quadratic term provide evidence of the EKC hypothesis in the globe, which indicates global CO_2 emissions initially increase and then decline after economic growth crosses a certain value, (i.e. turning point). Notably, both industrial structure upgrading and trade openness can reduce global CO_2 emissions, according to their negative coefficients in the empirical model. This is because both of them can accelerate the transformation of industrial structure from a carbon-intensive heavy industry to a low-carbon and high value-added service one. However, the positive estimated coefficients of population and urbanization level indicate positive correlations between population, urbanization level, and CO_2 emissions, respectively. Specifically, population promotes more CO_2 emissions mainly from two aspects: on the one hand, population growth results in more demand for energy consumption, especially for countries with low energy efficiency; on the other hand, rapid population growth may cause the destruction of forests and even change land utilization patterns, both of which are not conducive to carbon reduction. In terms of urbanization, the positive relationship between urbanization and CO_2 emissions reveals that the current urbanization process is not environmentally friendly. The reason might be that urbanization gives rise to more production and the establishment of more structures and industrial units, and the expansion of production necessitates more energy consumption, which would induce more CO_2 emissions.

Estimates for RCEP and Non-RCEP Countries

Table 6 exhibits the estimation results for the RCEP countries and non-RCEP countries. From the table, the *p*-values of the Hausman test statistics for the two subsamples reject the null hypothesis of the Hausman tests at the 1 and 5% significance levels, respectively. Thus, similar to the global panel above, the FE model is preferred as the benchmark estimation for both the RCEP and non-RCEP countries.

As for the RCEP countries, the coefficient of natural gas consumption is not significant, which indicates that increased natural gas consumption would not contribute to CO_2 emissions. This might be because several RCEP countries, (e.g. Japan, South Korea, and Singapore) have relatively foreign energy dependence, and this promotes these countries to have relatively higher technology levels. Furthermore, under the Kyoto Protocol and the Paris Agreement, these developed countries bear greater responsibility for reducing carbon emissions, which contributes

TABLE 7 | Results of the D-H panel causality tests.

No.	Null hypothesis	Global panel	RCEP countries	Non-RCEP countries
1	CO_2 ≠ NGC	7.5022***	−0.1402	7.5022***
2	NGC ≠ CO_2	11.0488***	3.8161***	11.0488***
3	CO_2 ≠ Tec	13.2951***	1.6112	13.2951***
4	Tec ≠ CO_2	10.3388***	10.1314***	10.3388***
5	NGC ≠ Tec	11.0120***	1.6314	11.0120***
6	Tec ≠ NGC	10.0630***	12.4269***	10.0630***

Notes: The values denote the Wald statistics, and A ≠ B *indicates that A does not cause B. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.*

a lot to the higher level of energy efficiency and technology development domestically. Thus, the signing of the RCEP would expand the technology spillovers among the relevant countries, which would neutralize the supposed positive effects of natural gas consumption on CO_2 emissions. However, after introducing the cross term of natural gas consumption and technological innovation into the empirical model, we find that natural gas consumption can significantly reduce CO_2 emissions, which further confirms the reinforcement effect of technology spillovers in the RCEP countries. It is also noteworthy that trade openness has a positive impact on CO_2 emissions in the RCEP countries. Thus, the signing of the RCEP would change the negative correlation between trade openness and CO_2 emissions. This may be because the signing of the RCEP would expand the volume of international trade of the relevant countries, thereby increasing production in a country, which would inevitably induce more energy consumption and CO_2 emissions. Therefore, at least in the short term, trade openness would contribute to CO_2 emissions in the RCEP countries, and this provides evidence for integrated environmental governance in the post-RCEP era. Additionally, the estimation results of other control variables are consistent with those for the global panel, which also coincides with the actual conditions of the RCEP countries.

With respect to the non-RCEP countries, the significance and signs of the estimated coefficients are similar to the estimation results for the full panel data. This may be because most global countries are different from the countries that sign the RCEP agreement. Thus, the estimation results for the non-RCEP countries are similar to that for the global panel, which state the general rule over the nexus between natural gas consumption, technological innovation, and CO_2 emissions. To conclude, the impact of natural gas consumption and technological innovation on CO_2 emissions is different between the RCEP and non-RCEP countries, which indicates significant heterogeneity in the natural gas-CO_2 nexus. Therefore, policymakers should formulate specific policies to reduce CO_2 emissions.

Results of the D-H Panel Causality Test

The results of the D-H panel causality test across different regions are displayed in **Table 7**. To clearly show the causality flows between natural gas consumption, technological innovation, and CO_2 emissions, this study also depicts the causality movements in **Figure 1**. As the figure shows, bidirectional causality runs between any two of the above three variables for the global panel data and the non-RCEP countries. However, for the RCEP countries, unidirectional causality runs only from technological innovation to CO_2 emissions, natural gas consumption to CO_2 emissions, and technological innovation to natural gas consumption, respectively.

On the one hand, the varying causal relationships between natural gas consumption, technological innovation, and CO_2 emissions again verifies the existence of heterogeneity in the natural gas-CO_2 nexus. On the other hand, policymakers should take the heterogeneous impact of natural gas consumption on CO_2 emissions into consideration and formulate specific policies to improve environment quality. For example, the technological spillover effects are reinforced in the RCEP countries, which provides evidence for policymakers to formulate policies to promote the development of technological innovation in the RCEP countries. Simultaneously, the positive correlation between trade openness and CO_2 emissions indicates that at least in the short term, trade openness would contribute to CO_2 emissions in the RCEP countries, which also suggests integrated environmental governance in the post-RCEP era.

CONCLUSION AND POLICY IMPLICATIONS

To investigate the impact of natural gas consumption on global CO_2 emissions and explore the role of technological innovation in the natural gas-CO_2 nexus, this study employs a balanced panel dataset for 73 countries for the period 1990–2019 for empirical analysis. Considering the cross-sectional dependence in the panel data, this study utilizes the FE and RE methods in the process of estimation. Furthermore, to examine heterogeneity in the nexus between natural gas consumption, technological innovation, and CO_2 emissions, we also conduct an empirical analysis for the RCEP countries and non-RCEP countries, respectively. This study makes several interesting findings, as follows:

First, natural gas consumption has a significant positive impact on global CO_2 emissions. However, technological innovation could reduce or even neutralize the environmental degradation effect of natural gas consumption to some extent. Specifically, the marginal impact of natural gas consumption on CO_2 emissions would decline with a higher level of technological innovation.

Second, this study verifies the EKC hypothesis between economic growth and global CO_2 emissions, by indicating an inverted U-shaped relationship between economic growth and global CO_2 emissions. That is to say, global CO_2 emissions increase initially and then decline after economic growth crosses a certain value, (i.e. turning point).

Third, heterogeneity exists in the natural gas-CO_2 emissions nexus between the RCEP countries and non-RCEP countries. The technological spillover effects are reinforced in the RCEP countries, which provides evidence for policymakers to formulate specific policies in a certain country. However, the positive correlation between trade openness and CO_2 emissions indicates that at least in the short term, trade openness would contribute to CO_2 emissions in the RCEP countries, which also suggests integrated environmental governance in the post-RCEP era.

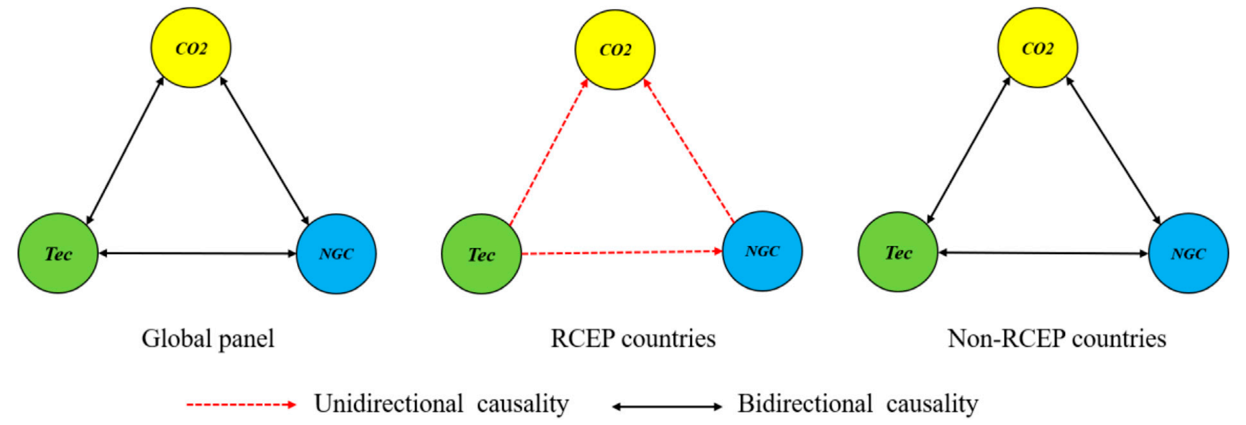

FIGURE 1 | Results of causality movements for the full panel and two subpanels.

Based on the above findings, several policy implications are highlighted as follows:

First, it is necessary to promote technological innovation, not only for its direct negative impact on global CO_2 emissions, but also for its spillover effect on the natural gas-CO_2 nexus. Thus, the governments should encourage enterprises to improve their production process, especially for cleaner technology advancement. For example, it is advisable to provide targeted subsides or tax reductions for technology research and development.

Second, given that the EKC hypothesis is valid in the globe, countries should continue to accelerate their economic growth and promote their economic structure into a low-carbon development mode. However, the COVID-19 epidemic which broke out at the end of 2019 has caused great damage to the world economy. Given that both technological innovation and trade openness can significantly reduce global CO_2 emissions, the technology trade deserves special attention to advance productivities for a post-epidemic "green recovery." For example, the global policymakers should encourage the development of technology trade among countries. Some effective measures include reducing the tariff to lower technology trade barriers, providing subsidies to encourage more technology trade. Furthermore, countries should strengthen environmental protection experience communication and cooperation, especially in the post-epidemic era where countries are closely linked with each other.

Third, considering that the technological spillover effects in the natural gas-CO_2 nexus are more reinforced in the RCEP countries, the relevant countries should attach more importance to technological innovation in the process of carbon reduction. Furthermore, given that trade openness would contribute to CO_2 emissions in the RCEP countries, the relevant countries should restrict the production of high-carbon products to guide the market and promote the development of high value-added and low-carbon industries, thereby realizing the transformation of trade structure to a low-carbon mode.

However, it is noteworthy that this study provides only preliminary empirical evidence on the natural gas-CO_2 emissions nexus, and some limitations still exist. One limitation is related to the specific impact mechanism between natural gas consumption and CO_2 emissions. In addition to the heterogeneous effects, in future research, we also can explore the mediating effect mechanism between natural gas consumption and global CO_2 emissions. Furthermore, it would be interesting to add more independent variables and estimate their potential impacts on global CO_2 emissions, such as foreign direct investment, industrialization, lifestyle change and so on; however, they are not considered in this study due to data missing in some countries. Additionally, since the RCEP agreement is signed not long ago, the data do not cover the period after the signing of the RCEP agreement. Thus, in future research, it will be interesting to employ a dataset that covers more updated data to examine whether the signing of the RCEP agreement can influence the nexus between natural gas consumption, technological innovation, and CO_2 emissions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YD:Conceptualization, Methodology, Validation, Investiga- tion, Writing - original draft, Writing—review and editing. JZ: Datacuration,Methodology,Software. JD:Conceptualization, Writing—review and editing.

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

TABLE A1 | The specific countries of RCEP and non-RCEP countries.

Region	Provinces
RCEP countries (12 countries)	Australia, China, India, Indonesia, Japan, South Korea, Singapore, New Zealand, Thailand, Philippines, Vietnam, Malaysia
Non-RCEP countries (61 countries)	Argentina, Australia, Brazil, France, Germany, Italy, Mexico, Netherlands, Russian federation, Saudi Arabia, Spain, Switzerland, Turkey, United Kingdom, United States, Denmark, Ukraine, Uzbekistan, Israel, Iraq, Iran, Bulgaria, Croatia, Canada, Hungary, North Macedonia, South Africa, Qatar, Luxembourg, Ecuador, Kazakhstan, Colombia, Turkmenistan, Venezuela, Bangladesh, Pakistan, Greece, Latvia, Norway, Czech Republic, Morocco, Slovakia, Slovenia, Chile, Belgium, Poland, Ireland, Estonia, Sweden, Belarus, Kuwait, Peru, Lithuania, Romania, Finland, Portugal, Azerbaijan, Algeria, Egypt, United Arab Emirates, Oman

TABLE A2 | Abbreviation list.

Abbreviations			
ADF	Augmented Dicky-fuller	FTA	Free trade Agreement
ASEAN	Association of Southeast Asian Nations	GDP	Gross domestic product
BP	British Petroleum	LM	Lagrange multiplier
CADF	Cross-sectionally augmented Dickey-fuller	LLC	Levin-Lin-Chu
CD	Cross-sectional dependence	Mt	Million tons
CIPS	Cross-sectionally augmented Im, Pesaran, and Shin	Mtoe	Million tons of equivalent oil
CO_2	Carbon dioxide	NGC	Natural gas consumption
D-H	Dumitrescu-Hurlin	PP	Phillips-Perron
EKC	Environmental Kuznets curve	RCEP	Regional Comprehensive Economic Partnership
FDI	Foreign direct investment	RE	Random effect
FE	Fixed effect	US	United States