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Are Energy Consumption, Population Density and Exports Causing Environmental Damage in China? Autoregressive Distributed Lag and Vector Error Correction Model Approaches

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Abstract: This paper investigates whether energy consumption, population density, and exports are the main factors causing environmental damage in China. Using annual data from 1971–2018, unit root tests are applied for the stationarity analyses, and Autoregressive Distributed Lag (ARDL) bounds tests are used for the long-run relationships between the variables. A Vector Error Correction Model (VECM) Granger approach is employed to examine the causal relationships amongst the variables. Our findings show that the selected variables are cointegrated, and that energy consumption and economic growth are identified as the main reasons for CO_2 emissions in both the short-run and long-run. In contrast, exports reduce CO_2 emissions in the long-run. Short-run unidirectional Granger causality is found from economic growth to energy consumption, CO_2 emissions and exports, and from CO_2 emissions to energy consumption and exports. Moreover, long-run causal links exist between CO_2 emissions and exports. Five policy recommendations are made following the obtained results.

Keywords: CO_2 emissions; energy consumption; population density; exports; energy economics; China

JEL Classification: Q43; Q53; Q56; C22; O44

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1. Introduction

China has attained remarkable achievements in a number of important areas during the last several decades. The real Gross Domestic Product (GDP, constant 2010 USD) per capita of China increased dramatically from USD 191.8 in 1960 to USD 8254 in 2019. The poverty headcount ratio of USD 1.9 a day decreased rapidly from 42.5% in 1981 to 9.2% in 2017. China is also the most populous country, with 1.44 billion people in 2020 [1], the highest consumer of energy, and the largest contributor of CO_2 emissions, with 24% of global energy consumption and 29% of total CO_2 emissions in 2018 [1]. The CO_2 emissions of China (metric tons per capita) increased significantly, from 1.17 in 1960 to 7.95 in 2018 [1,2]. Therefore, it is useful to explore the causative factors of CO_2 emissions in China.

A number of previous studies have identified energy consumption, economic growth, financial development, foreign direct investment, and trade openness as the major causative factors for environmental damage across countries; however, no previous studies, to the best of our knowledge, have investigated whether population density, along with other factors, is the main reason for environmental damage in China. Greater population means more human activities and a greater demand for industrial production, transport, and energy consumption that result in environmental degradation via increased CO_2 emissions and huge amounts of waste [3]. Furthermore, export, rather than total trade or trade openness, is a more appropriate variable to consider in carbon analysis, because one-third of China's CO_2 emissions are caused by exports [4]. Surprisingly few studies in the past have explored the true effect of this variable on CO_2 emissions. In this research, we have explored the roles of these two variables to fill the gaps in the literature. Hence, the novelty of this research is to explore the environmental effects of these two variables, which were previously ignored by other researchers. Our central question of investigation is: do these two new variables play any role in the environmental quality of China, along with other variables?

With this objective in mind, we have examined the effects of energy consumption, economic growth, exports, and population density on CO_2 emissions (proxy for environmental quality) in China using the autoregressive distributive lag (ARDL) bounds tests and the VECM Granger causality technique. The main contributions of this study are as follows: (i) We add population density and exports as new variables to provide evidence of the linkages between economic growth, energy consumption, population density, exports, and CO_2 emissions in China, in both the short- and long-run, which are limited in the literature to date; (ii) we conduct necessary diagnostic tests for checking the stationarity of variables, the reliability of the model, the stability of coefficients/results along with normality, and the serial correlation and heteroscedasticity tests; (iii) finally, we have initiated discussions for China on whether it should aim for continuous increased production using nonrenewable energy, or whether it should limit its growth aspirations by achieving sustainable production using more renewable energy and energy efficient technologies.

This study is important for the policy makers of China and other countries to understand the complex nexus between energy consumption, population density, exports, economic growth, and environmental quality for formulating effective policies for development. For instance, if population density and exports do adversely affect CO_2 emissions, the government should redesign its trade policy for desired exports and do likewise with its population policy to have an optimum population by birth control and/or controlling migration. Similarly, if economic growth and energy consumption increase CO_2 emissions, limiting growth targets by optimum production, and less use of nonrenewable energy and energy-inefficient technologies, would be effective options. Despite the negative impacts of the COVID-19 pandemic on the Chinese economy, it may be a new opportunity to restructure industries towards a digital and green economy, rather than restart traditional industries.

The paper is organized as follows. Section 2 shows a brief literature review on the key factors causing environmental damage across countries. Section 3 outlines the materials and methods. Section 4 presents and discusses the study's empirical results, and Section 5 draws conclusions.

2. Literature Review

Some studies on the determinants of CO_2 emissions have been conducted across countries; however, the findings are diverse, mainly due to the use of different methodological approaches and variables, data periods, and heterogeneous country characteristics. In this paper we will review past studies under four strands of research.

2.1. CO_2 Emissions and Economic Growth Nexus

The theoretical framework of the Environmental Kuznets Curve (EKC) hypothesis is tested by the nexus between CO_2 emissions and economic growth. According to this hypothesis, EKC is a nonlinear inverted U-shaped curve that explains that environmental degradation rises initially with the increase of economic growth, and then starts to decline when economic growth reaches a threshold with a high level of income [5]. This hypothesis implies that, in the long-run, economic growth brings welfare for the environment [6]. Although this hypothesis has been empirically tested by many researchers in single and cross-country studies, the researchers were unable to reach a conclusive agreement. For example, recent studies, such as those of Sarkodie and Ozturk [7], Rahman and Velayutham [8], Rahman, Murad [9], Shahbaz, Nasir [10], Zoundi [11], Lean and Smyth [12], Tiwari, Shahbaz [13], Ertugrul, Cetin [14], Kanjilal and Ghosh [15], and Sephton and Mann [16], found evidence of the existence of the EKC hypothesis. However, some studies, such as those of Rahman [17], Arouri, Youssef [18], Ozturk and Acaravci [19], Musolesi, Mazzanti [20], Pao, Yu [21], He and Richard [22], and Tunç, Türüt-Aşık [23], could not find compelling evidence for this hypothesis. Rahman [17] found a U-shaped relationship; Tunç, Türüt-Aşık [23], Kashem and Rahman [24], Arouri, Youssef [18], and Musolesi, Mazzanti [20] revealed an increasing long-run linear relationship between economic growth and CO_2 emissions. Ozturk and Acaravci [19] and Musolesi, Mazzanti [20] found evidence of a U-shaped relationship between these two variables.

2.2. CO_2 Emissions, Economic Growth and Energy Consumption Nexus

The nexus between CO_2 emissions, economic growth, and energy consumption, as discussed in the current empirical literature, is also not uniform. For example, Alam, Begum [25], Appiah [26], Alam, Begum [27], Koengkan, Losekann [28], and Koengkan, Fuinhas [29] found a bidirectional causal link between CO_2 emissions and energy consumption for India, Ghana, Bangladesh, four Andean community countries and five countries, including Argentina, Brazil, Paraguay, Uruguay, and Venezuela, respectively. However, no causality between economic growth and CO_2 emissions was found in India, though a unidirectional causality running from CO_2 emissions to economic growth was found in Bangladesh. On the other hand, some studies revealed the existence of unidirectional causality from economic growth to energy consumption and CO_2 emissions (see Rahman and Kashem [30] for Bangladesh, Khan, Khan [31] for Pakistan, Uddin, Bidisha [32] for Sri Lanka, Kasman and Duman [33] for the EU members and candidate countries, Shahbaz, Hye [34] for Indonesia, and Hossain [35] for Japan). In addition, Adedoyin and Zakari [36] found a unidirectional causality from energy consumption to CO_2 emissions for the United Kingdom. Likewise, positive effects of economic growth and energy consumption on CO_2 emissions were confirmed by the studies of Balsalobre-Lorente, Shahbaz [37] for EU-5 countries, Ahmed, Bhattacharya [38] for ASEAN-8 countries, Begum, Sohag [39] for Malaysia, Tang and Tan [40] for Vietnam, and Alam, Murad [6] for other four countries. In Tunisia, Mbarek, Saidi [41] found a causal nexus between energy consumption and CO_2 emissions. In contrast, Soytas, Sari [42] did not find any causal relationship between economic growth and CO_2 emissions, and between energy and economic growth, in the USA.

2.3. CO_2 Emissions and Population Density Nexus

Very few studies exist in the literature that examine the impact of population density/growth on CO_2 emissions, though environmental quality is affected by population growth. Engelman [43] and O'Neill, MacKellar [44] opined that population growth is one of the major factors for CO_2 emissions in all countries, irrespective of levels of development. Empirically, Mamun, Sohag [45] explored the link between population growth and CO_2 emissions, controlling for some other variables, for a total of 136 countries, and revealed that population size increased CO_2 emissions in the long-run. Ohlan [46] also indicated a significant positive impact of population density on CO_2 emissions in India in short- and long-runs. In contrast, Chen, Wang [47] found that population density would reduce air pollution in China. Rahman, Saidi [48] revealed a unidirectional causality from population density to CO_2 emissions for South Asia. Moreover, in a study on 93 countries, Shi [49] demonstrated that 1.28% of CO_2 emissions are linked with 1% population growth, and that the extent of the impact of population increase on CO_2 emissions is greater in developing countries than in developed countries.

2.4. CO_2 Emissions–Trade/Exports Nexus

Theoretically, the net effect of international trade on environmental quality could either be beneficial or detrimental for the environment [17]. The supporters of a beneficial effect argue that free trade enables countries to have greater access to broader international markets. As a result, competition, power, and efficiency of countries are increased, which facilitates the import of cleaner technologies and, thus, lower carbon emissions [34,50]. On the other hand, negative arguments are raised by some researchers due to the fact that increased exports lead to increased industrial production activities, which ultimately increase CO_2 emissions and, hence, damage environmental quality [51]. Empirically, Jebli, Youssef [52], Balsalobre-Lorente, Shahbaz [37], Gasimli, Gamage [53], Mahmood, Maalel [54], Murad and Mazumder [55], Tiwari, Shahbaz [13], and Halicioglu [56], found detrimental effects of trade on the environment in 22 Central and South American countries, 5 EU countries, as well as Sri Lanka, Tunisia, Malaysia, India, and Turkey. In contrast, Khan, Ali [57] demonstrated that exports decreased and imports increased consumption-based carbon emissions in nine oil-exporting countries. Similar findings are also found by Muhammad, Long [58] for 65 Belt and Road initiative countries. Furthermore, Haq, Zhu [59] and Shahbaz, Lean [60] found evidence of the beneficial effects of trade in Morocco and Pakistan. Likewise, Kasman and Duman [33] and Rahman, Saidi [61] investigated the causal relationship between trade openness and CO_2 emissions in new EU member and candidate countries and three developed countries, although Haug and Ucal [62] and Hasanov, Liddle [63] found no or weak effects in Turkey and oil-exporting countries.

The forgoing discussion exhibits the contradictory nature about the responsible factors for CO_2 emissions across countries. Therefore, country-specific studies focusing on appropriate variables, such as population density, are important to mitigate the current debate.

3. Materials and Methods

3.1. Theoretical Notions and the Model

The objective of our research was to investigate the impacts of population density, along with economic growth, energy consumption and export production, on CO_2 emissions in China during the period 1971–2018. As energy consumption and economic growth may cause CO_2 emissions [32,34,64] we included them in our model. We also added population density in our model because more people means higher demand for energy for elasticity, industrial activities, and transportation, all of which cause CO_2 emissions [39,61]. In addition, we included export as a variable in our model, since it may affect environmental quality due to government policies, or may increase the income of developing countries and induce them to use/import environmentally friendly technology to promote production [34].

The rationale for selecting these variables is further discussed as follows. Kuznets [65] proposed that income disparity initially increases and declines with economic growth. The inclusion of economic growth in CO_2 emissions analysis is based on the environmental Kuznets curve (EKC) hypothesis, which suggests that economic growth and environmental quality have an inverted U-shaped relationship. At the initial stages of industrialization and development, pollution levels increase with growth; however, growth may decrease pollution when countries are rich enough to pay for energy efficient and environment friendly technologies. Therefore, the model is constructed in a quadratic form of real GDP per capita.

In the same vein as capital and labor, energy is considered one of the important inputs of production. It is a vital instrument of socioeconomic development [66]. Energy consumption can both pollute the environment through the use of fossil fuels and improve environmental quality by renewable energy consumption. Fossil fuels are the major portion of energy use. For production activities, use of more machinery is needed, which requires more energy, emitting a greater amount of CO_2 emissions in the atmosphere. In contrast, a number of alternative types of energy sources (e.g., wind, solar energy, nuclear power plants) do not add greenhouse gases to the atmosphere. Using these low carbon energy sources can reduce CO_2 emissions.

High population density may cause several environmental impacts (see Section 2.3). For example, high population density can cause the depletion of natural resources (arable land, water, forest, energy, etc.) and degradation of the environment due to overuse of nonrenewable energy, for example, coal, oil, and natural gas [3].

From a theoretical point of view, the environmental impacts of international trade can be either positive or negative. Environmentalists believe that international trade affects the environment negatively, at least in the short-run, via international specialization in intensive polluting products, the acceleration of trade with hazardous substances and waste, and extensive transport use for long distances [67]. On the other hand, the positive effects of international trade on the environment are explained by the rationale that trade generates wealth and increases the movement of environmental technologies between countries [68]. As a result, a higher standard of living leads to higher demand for a cleaner environment, which will ultimately result in environmental improvement [69]. Although many previous studies included imports alongside exports (international trade) for CO_2 emissions analysis (see Section 2.4), we argue that imported products/services may directly affect the environment of exporting countries rather than the environment of importing countries [4,51,70]. Therefore, our study employed export production for CO_2 emissions analysis.

Therefore, the following empirical linear model was constructed:

$$C_t = f(E_t, G_t, G_{t,}^2 P_t, X_t) \tag{1}$$

Model 1 is transformed into a logarithm to eliminate potential heteroscedasticity issues and gain direct elasticities, and can be rewritten as follows:

$$LnC_t = \alpha_0 + \alpha_E \ln E_t + \alpha_G LnG_t + \alpha_{G^2} LnG_t^2 + \alpha_P LnP_t + \alpha_X LnX_t + \mu_t \tag{2}$$

where C_t is CO_2 emissions per capita, E_t is energy consumption per capita, G_t ($G_t{}^2$) is real GDP (squared) per capita used as a proxy for economic growth, P_t is population density, X_t is export per capita, and μ_t is the error term.

We assumed that a rise in energy consumption and population density may cause higher CO_2 emissions. Therefore, α_E, and α_P were expected to be greater than zero. The EKC hypothesis suggests that $\alpha_G > 0$ whereas $\alpha_{G^2} < 0$.

In contrast, a rise in exports may negatively affect CO_2 emissions ($\alpha_{TR} < 0$) if there is a decrease in production of pollutant intensive items because of environmental protection laws, or positive ($\alpha_{TR} > 0$) if more intensive polluting production is undertaken, causing more CO_2 emissions.

As China initiated its "Open Door policy" in late 1978, became a member of the World Trade Organization in December 2001 [71], and officially ratified the Kyoto Protocol in August 2002 [72], we included a dummy variable (D_t, i.e., D_{1978} and D_{2002}) in our model to take structural effects into account. As a consequence, the model (2) was reconstructed as follows:

$$LnC_t = \alpha_0 + \alpha_E \ln E_t + \alpha_G LnG_t + \alpha_{G^2} LnG_t^2 + \alpha_P LnP_t + \alpha_X LnX_t + D_t + \mu_t \tag{3}$$

3.2. Unit Root Tests

The first requirement for time series data is to test the stationarity of selected variables. We applied the unit root test, proposed by Dickey and Fuller [73] and developed by Elliott, Rothenberg [74], to investigate the stationarity properties of our selected variables (see Figure 1).

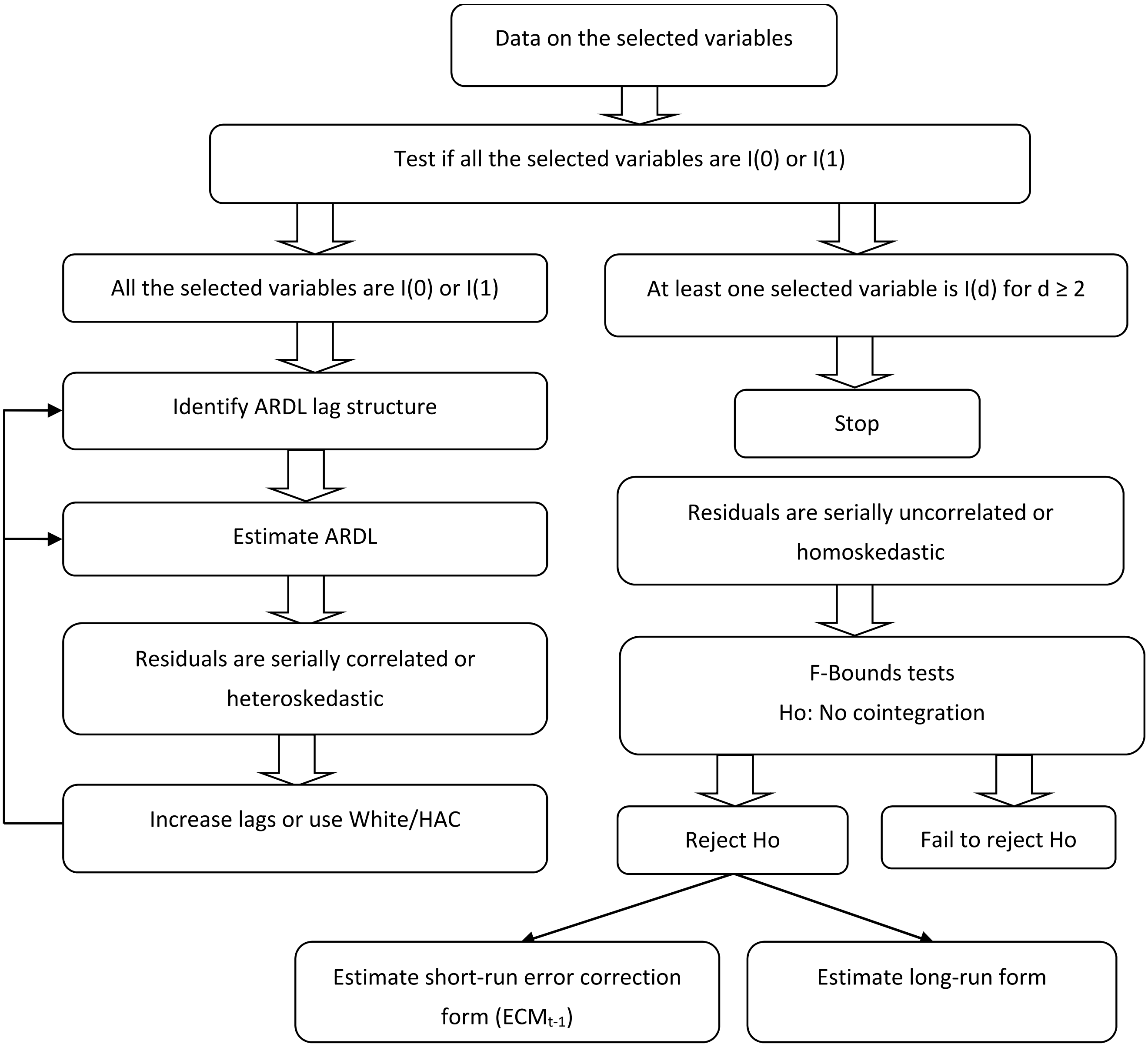

Figure 1. A flowchart summary of the stationarity tests in Section 3.2 and the cointegration tests in Section 3.3.

3.3. Cointegration Tests

The autoregressive distributive lag (ARDL) bounds tests developed by Pesaran, Shin [75] was used to explore the cointegration for a long-run association between CO_2 emissions, energy consumption, economic growth, population density, and export in China. These tests have the following advantages: (1) bounds tests can be conducted with a mixture of I(0) and I(1) processes [76]; (2) the tests comprise a single-equation setup [75]; (3) the ARDL bounds tests decompose error terms, and multicollinearity are eliminated by taking differencing of data [77]; (4) a sufficient number of lags lengths can be assigned, and the automatic lag specification in the ARDL framework is used to remove any multicollinearity and endogeneity problems [78,79].

The ARDL bounds tests were undertaken as follows. The joint F-statistic was used to test the null hypothesis of no cointegration. If the calculated F-statistic was below the lower bound of critical value, the null hypothesis failed to be rejected. If the calculated F-statistic was above the upper bound of critical value, the null hypothesis was rejected.

If the calculated F-statistic was between the upper and lower limits of critical value, no conclusion could be made.

The ARDL method included two steps for estimating the long-run relationship. The first step consisted of testing the long-run association amongst all selected variables. If a long-run relationship exists between the variables, the second step was to estimate the long-run model with the least squares, and short-run error correction model. The ARDL long-run and ARDL short-run forms are expressed in Equations (4) and (5), respectively. Model 5 was only valid if the coefficient of lagged error term ($\mathrm{ECM}_{\mathrm{t}-1}$) was negative and significant. In addition, $\mathrm{ECM}_{\mathrm{t}-1}$ suggests the speed of convergence from short-run towards the long-run equilibrium path (see Figure 1).

$$LnC_t = \alpha_0 + \alpha_E LnE_{t-i} + \alpha_G LnG_{t-i} + \alpha_{G^2} LnG^2_{t-i} + \alpha_P LnP_{t-i} + \alpha_{TR} LnX_{t-i} + \mu_t \tag{4}$$

$$\Delta LnC_t = \alpha_0 + \alpha_E \Delta LnE_{t-i} + \alpha_G \Delta LnG_{t-i} + \alpha_{G^2} \Delta LnG^2_{t-i} + \alpha_P \Delta LnP_{t-i} + \alpha_{TR} \Delta LnX_{t-i} + D_t + \delta_0 ECM_{t-1} + \varepsilon_t \tag{5}$$

We also applied the approach by Johansen [80] and Johansen [81] to test the robustness of ARDL bounds test for the long-run relationship.

3.4. Model Stability and Diagnostic Tests

We used stability tests, including the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals (CUSUMSQ), developed by Brown et al. (1975) [82] and Pesaran and Pesaran (1997). If the CUSUM and CUSUMSQ statistics were within the 5% critical boundaries, the long-run and short-run parameters in our models were stable and could not be rejected. To examine the goodness of fit of our ARDL models, we conducted diagnostic tests, including a normality test, a Heteroskedasticity test, a Breusch–Godfrey Serial Correlation LM test, and a Ramsey RESET.

3.5. Granger Causality Tests

As the ARDL cointegration approach does not explore the direction of causality among CO_2 emissions, energy consumption, economic growth, population density, and export, we used the VECM Granger causality tests [83] to examine the direction of causality amongst the selected variables. Granger [83] argued that, with the existence of cointegration, the VECM Granger causality tests are appropriate to explore the long-run and short-run causal relationships between the CO_2 emissions, energy consumption, population density, economic growth, and exports (see Figure 2). The VECM model is demonstrated as follows:

$$\begin{bmatrix} LnC_t \\ LnE_t \\ LnG_t \\ LnG_t^2 \\ LnP_t \\ LnX_t \end{bmatrix} = \begin{bmatrix} \beta_1 \\ . \\ . \\ . \\ . \\ \beta_6 \end{bmatrix} + \begin{bmatrix} a_1 \ldots . a_n \\ . \\ . \\ . \\ . \\ a_6 \ldots . a_n \end{bmatrix} + \begin{bmatrix} LnC_{t-1} \\ LnC_{t-2} \\ LnC_{t-3} \\ LnC_{t-4} \\ LnC_{t-5} \\ LnC_{t-6} \end{bmatrix} + \ldots .. \begin{bmatrix} \delta_1 \ldots . \delta_n \\ . \\ . \\ . \\ . \\ \delta_6 \ldots . \delta_n \end{bmatrix} + \begin{bmatrix} LnX_{t-1} \\ LnX_{t-2} \\ LnX_{t-3} \\ LnX_{t-4} \\ LnX_{t-5} \\ LnX_{t-6} \end{bmatrix} + \begin{bmatrix} \gamma_t \\ . \\ . \\ . \\ . \\ \gamma_t \end{bmatrix} ECM_{t-1} + \begin{bmatrix} \varepsilon_t \\ . \\ . \\ . \\ . \\ \varepsilon_t \end{bmatrix} \tag{6}$$

where $\beta, a, \delta, and\ \gamma$ are coefficients; and ε is white noise.

3.6. Data Sources

The data on CO_2 emissions (metric tons) per capita and energy consumption (kg of oil equivalent) per capita were collected from the World Development Indicators [84] and Statistical Review of World Energy [85]. The population density (people per square km of land area), economic growth (GDP per capita at constant 2010 USD), and exports of goods and services per capita (constant 2010 USD) were collected from the World Development Indicators [84]. The data period of the current study is 1971–2018, where annual observations are used.

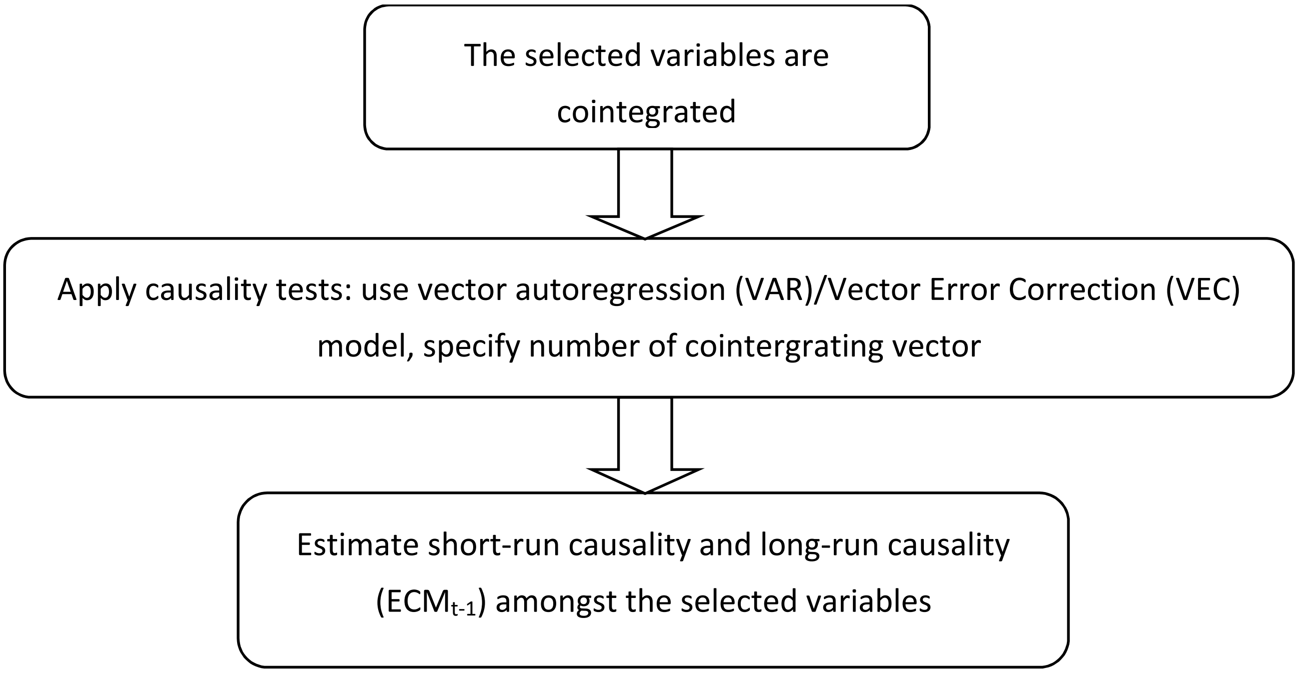

Figure 2. Shows the approach of the causality tests in Section 3.5.

3.7. Preliminary Examinations of Data

All variables were transformed into natural logarithms. A summary statistic of the variables used in this study is presented in Table 1. Table 1 shows that all the variables have normal distribution, as confirmed by a Jarque–Bera test. The minimum and maximum values of CO_2 emissions, economic growth, and exports per capita are noticeable. The lowest value of CO_2 emissions is 0.04, the highest value is 1.92; the minimum value of export per capita is 1.89, the maximum value is 7.32; and the minimum value of growth variable is 5.47, while the maximum value is 8.95. Figure 3 indicates the upward trends of the CO_2 emissions, energy consumption, GDP per capita, population density, and trade per capita in China from 1971 to 2018. Growth was continuous over the sample period and rose sharply, especially after 1979. A sharp rising trend of energy consumption and CO_2 emissions, especially after 2001, was also noticeable.

Table 1. Descriptive statistics.

	LnC	**LnE**	**LnG**	**LnG^2**	**LnP**	**LnX**
Mean	1.0020	6.8528	7.0830	51.4217	4.8100	5.0882
Median	0.9581	6.7347	7.0640	49.9030	4.8492	5.3625
Maximum	1.9177	7.7623	8.9560	80.2115	4.9995	7.3220
Minimum	0.0413	6.1418	5.4740	29.9653	4.4952	1.8942
Std. Dev.	0.6067	0.5116	1.1309	16.2120	0.1501	1.7830
Jarque–Bera	3.1937	4.5296	3.5246	3.6910	4.2287	3.8862
Probability	0.2025	0.1038	0.1716	0.1579	0.1207	0.1432

Note: There is no missing variable during the study period 1971–2018 (48 years). (Source: Authors' calculations).

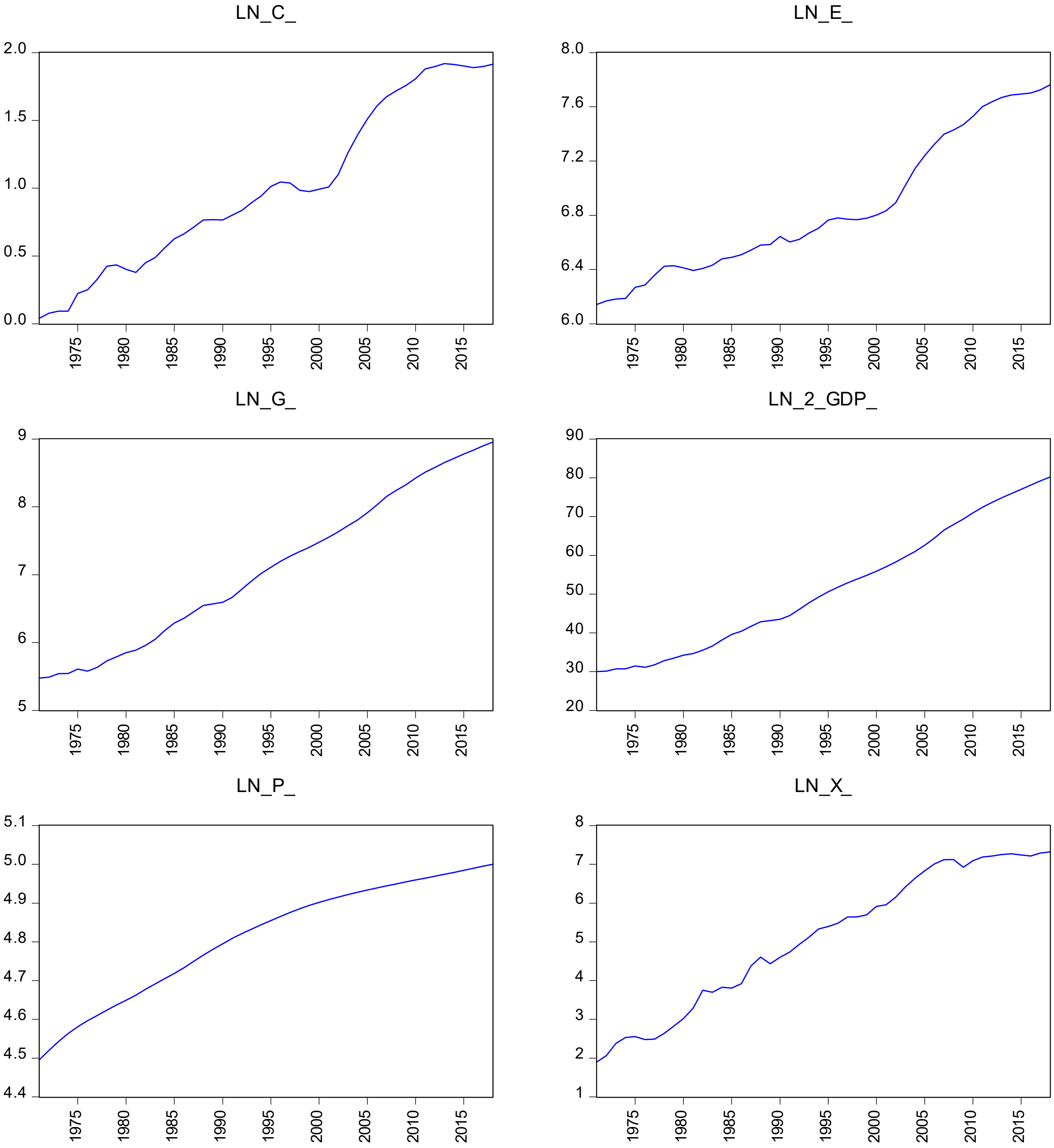

Figure 3. Trend lines of logarithms of CO_2 emissions, energy consumption, GDP per capita, population density, and exports per capita in China from 1971 to 2018. (Source: Authors' calculations).

4. Findings and Discussions

4.1. The Findings of Unit Root Tests

The results of unit root tests [74] indicate that all the variables of interest show unit root problems at their level, but are found to be integrated at I(1) (see Table 2). Therefore, we applied the ARDL bounds tests to investigate the long-run relationship between CO_2 emissions, energy consumption, population density, economic growth, and exports for the period of 1971–2018.

Table 2. Dickey–Fuller GLS Unit Root Test.

Variables	At Level	At 1st Difference
	T-Statistic	**T-Statistic**
LnC	−2.8614 (1)	−3.5837 (0) **
LnE	−1.6222 (1)	−3.8906 (0) ***
LnG	−1.9098 (2)	−3.2900 (1) **
LnG^2	−1.1937 (1)	−3.3910 (1) **
LnP	−1.2731 (5)	−3.2052 (3) ***
LnX	−0.8788 (0)	−5.8145 (0) ***

Notes: lag order is presented in parentheses; constant and linear trends are chosen. *** and ** denote significant at 1% and 5% levels of significance, respectively. (Source: Authors' calculation).

4.2. The Results of Cointegration Tests

As the choice of lag length can affect the F-test, it is necessary to choose the proper lag order of the variables before applying ARDL bounds tests. We chose the automatic selection of lag length for our dependent variable (CO_2 emissions) and independent variables (energy consumption, economic growth, population density, and exports).

The results of the ARDL bounds tests [75] for the long-run relationship between the selected variables show that the calculated F-statistic is significant at 5% if CO_2 emission is a dependent variable. In addition, the calculated F-statistics are significant at 1% if energy consumption, economic growth, and population density are dependent variables, respectively. The diagnostic tests' findings demonstrate the validity of the estimation (Table 3). For example, the results of the diagnostic tests show that the model passes all tests, demonstrating no issues with normality, heteroskedasticity, serial correlation, and omitted variables. As the ARDL bounds tests decompose error terms, multicollinearity issues are eliminated by taking the differencing of data [77]. To save space, we report the findings of the ARDL bounds test for CO_2 emissions as a dependent variable (Table 3). The findings of the ARDL bounds test for energy consumption, economic growth, population density, and exports, as dependent variables, are made available upon request.

Table 3. ARDL bounds test for cointegration.

Estimate Equation	$C_t = f(E_t, G_t, G_t^2, P_t, X_t)$	
F-statistics	3.9345 **	
Significance level	Critical value (T = 48)	
	Lower bounds, I(0)	Upper bounds, I(1)
1%	3.674	3.297
5%	2.694	3.829
10%	2.276	5.019
Diagnostic tests		Statistics (*p*-value)
Adjusted-R^2		0.9756
Normality test		0.1043
Heteroskedasticity Test: ARCH		0.1613
Breusch–Godfrey Serial Correlation LM Test		0.1123
Ramsey RESET		0.5245

Note: ** represents significant at 5%. (Source: Authors' calculations).

To check the robustness of the ARDL bounds test results, we furthermore used the Johansen's cointegration tests [81]. The results of the trace test and the maximum eigen value tests [81] (Table 4) are consistent with the findings of the ARDL bounds tests [75]. Hence, we rejected the null hypotheses of no cointegration, and the variables of interest are cointegrated for a long-run relationship.

Table 4. Results of the Johansen's cointegration tests.

Hypothesised no. of Cointegrated Equation(s)	Trace Statistic	*p*-Value (Trace Test)	Max-Eigen Statistic	*p*-Value (Max-Eigen Test)
None *	200.8215	0.0000	74.8339	0.0000
At most 1 *	125.9875	0.0000	47.8554	0.0006
At most 2 *	78.1321	0.0000	37.8395	0.0017
At most 3 *	40.2925	0.0022	22.2696	0.0345
At most 4 *	18.0229	0.0204	14.2646	0.0471
At most 5	3.5946	0.0580	3.8414	0.0580

Notes: * the results of trace and max-eigenvalue tests provide evidence of cointegration for long-run relationships among the selected variables at least 5%. (Source: Authors' calculations).

4.3. The Long-Run and Short-Run Analyses

We investigated the marginal impacts of energy consumption, population density, economic growth, and exports on CO_2 emissions. The long-run analyses (Table 5) indicate that energy consumption positively and significantly affects CO_2 emissions. For instance, a 1% rise in energy consumption, keeping other factors constant, leads to a 1.35% increase in CO_2 emissions. This result is consistent with Balsalobre-Lorente, Shahbaz [37], Ahmed, Bhattacharya [38], Jalil and Mahmud [86], Ang [87], Say and Yücel [88], Halicioglu [56], and Hamilton and Turton [89]. In contrast, a 1% rise in exports is associated with a 0.15 decline in CO_2 emissions. The negative sign for exports may be interpreted as demonstrating that China has used more environmentally friendly technologies for its export production. This finding is consistent with Haq, Zhu [59] and Shahbaz, Lean [60], who suggest that exports may decrease CO_2 emissions as a result of positive technological effects. In addition, the time trend shows that CO_2 emissions declined by 0.04% when there was a 1% increase in technology improvement.

Table 5. Long-run and short-run analyses.

Dependent Variable = lnC_t	**Coefficients**	**T-Statistics**
	Long-run analysis	
Constant	−13.8384 ***	−7.2486
$\ln E_t$	1.3505 ***	16.6183
$\ln G_t$	2.3237 ***	5.0201
$\ln {G_t}^2$	−0.1460 ***	−6.5597
$\ln P_t$	−0.5576	0.8100
$\ln X_t$	−0.1556 **	−3.4227
Time trend (t)	−0.0461 ***	−6.8920
	Dependent variable = $\Delta\ln C_t$ Short-run analysis	
$\Delta\ln E_t$	0.3814 ***	4.8119
$\Delta\ln G_t$	3.5963 ***	6.0981
$\Delta\ln G^2{}_t$	−0.1844 ***	−4.1916
$\Delta\ln P_t$	−7.5719	−2.0609
$\Delta\ln X_t$	−0.0322	−1.4846
D_{1978}	−0.0236	−1.6491
D_{2002}	0.0327 **	2.6126
ECM_{t-1}	−0.2777 ***	−7.1518

Note: *** and ** indicate significant at 1% and 5%, respectively. (Source: Authors' calculations).

Of a particular interest is that both linear and nonlinear forms of real GDP show evidence in supporting an inverted-U relationship between economic growth and CO_2 emissions. The findings show that, in the long-run, a 1% increase in real GDP raises CO_2 emissions by 2.23%, whereas the negative sign of the squared form of real GDP supports the delinking of real GDP and CO_2 emissions. The calculated turning point of real GDP per capita was USD 7688, compared to the highest value in our sample of USD 7755 (graphical presentation is made available upon request). These findings are in line with the EKC hypothesis that CO_2 emissions rise in the initial period of economic growth and decrease after a threshold point. The findings are in line with Sarkodie and Strezov [90], Jalil and Mahmud [86], Diao, Zeng [91], Riti, Song [92], Rahman and Velayutham [8], Shahbaz, Nasir [10], Zoundi [11], Tao, Zheng [93], He [94], and Fodha and Zaghdoud [95].

The short-run dynamics findings are shown in Table 5. The results indicate that a 1% rise in energy consumption is significantly associated with a 0.4% rise in CO_2 emissions; however, the short-run energy consumption elasticity for CO_2 emissions (0.4) is much less than the long-run elasticity for CO_2 emissions (1.35). The coefficients of real GDP and GDP^2 also provide evidence of an inverted-U Kuznets curve in the short-run. In addition, the short-run squared income elasticity for CO_2 emissions (in absolute value) is greater than the long-run elasticity for CO_2 emissions; this finding further demonstrates the presence of an inverted-U Kuznets curve. The impacts of energy consumption and economic growth (real GDP squared ${G_t}^2$) in the short-run may be interpreted as indicating that the Chinese government, for the first time in 2007, emphasized the quality rather than the quantity of economic growth [96]. The 2007 Chinese Communist Party Congress called on all sectors, industries, and people in China to change their behaviors to protect the environment [96]. The government also started promoting energy-efficient technologies in the construction and mining sectors, as well as subsidized energy-efficient lighting products and automobiles. It also offered a variety of financial supports and taxes for customers who traded in energy-inefficient products for new, energy-saving ones. In addition, the lower significant positive sign of energy consumption can be explained by the fact that China has recently consumed more renewable energy (short-run). Since 2008, China has issued regulations on renewable energy, water pollution, chemical substances and electronic waste, and emissions and pollution standards [96]. Our finding is consistent with that of Li and Yang [97] who indicated that, to mitigate CO_2 emissions, China has developed renewable and nuclear energy resources to substitute for traditional fossil fuels, as well as created energy policies to promote clean energy consumption. Non-fossil energy consumption in China increased from 3.8% in 1965 to 10.9% in 2014. In addition, China plans to raise the share of non-fossil energy in the energy mix to around 20% by 2030. Therefore, the increasing use of renewable energy in recent years may be one of the key factors for the lower energy consumption elasticity for CO_2 emissions in China.

The dummy variable (D_{2002}) is significant at 5%. This suggests that CO_2 emissions in China increased by 3.3% per year after China joined the WTO in December 2001, although it officially ratified the Kyoto Protocol in August 2002. This may be explained by the fact that China considerably promoted its production for both domestic and foreign markets after it became a member of the WTO [98].

Table 5 shows that the lagged error term (ECM_{t-1}) is -0.28 and statistically significant at 1%. This demonstrates evidence of the long-run relationship between the selected variables. The coefficient indicates that the change in CO_2 emissions in China is corrected by 28% per year in the long-run. This implies that the full convergence process may take approximately four years to achieve a stable path of equilibrium, and the adjustment process is fairly fast.

Our results also indicate that, amongst the variables estimated, energy consumption and economic growth (real GDP) are the main factors for CO_2 emissions in China in both the short- and long-runs. These findings are consistent with the theory, as expected, and are similar to the findings by Shahbaz, Hye [34], Tang and Tan [40], and Rahman [17]. Surprisingly, the short-run and long-run coefficients of population density are negative; however, they are statistically insignificant. The short-run coefficient of exports is negative but insignificant.

The plots of CUSUM and CUSUMSQ statistics are well within the 5% critical boundaries (Figures 4 and 5), demonstrating that all the long- and short-run parameters in our model are stable.

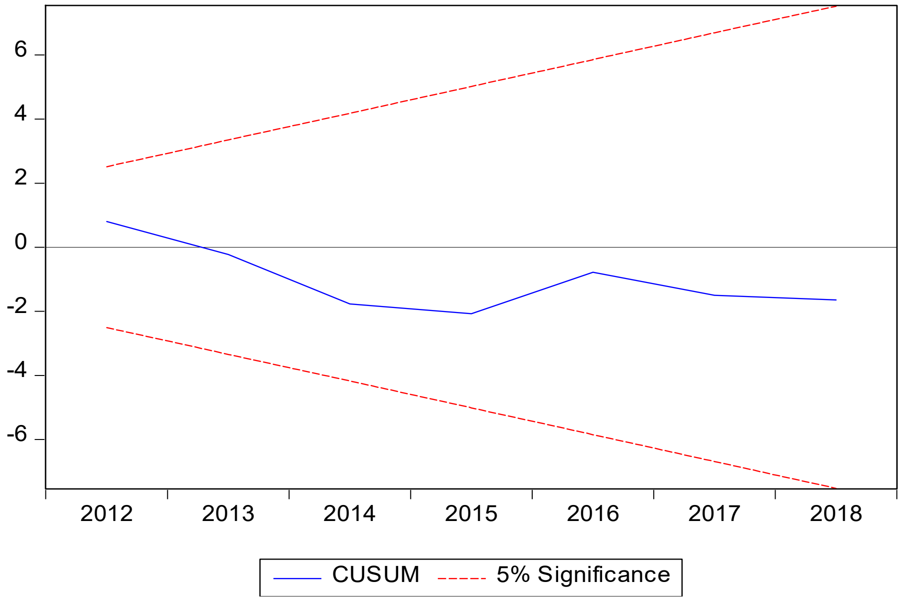

Figure 4. Plot of cumulative sum of recursive residuals.

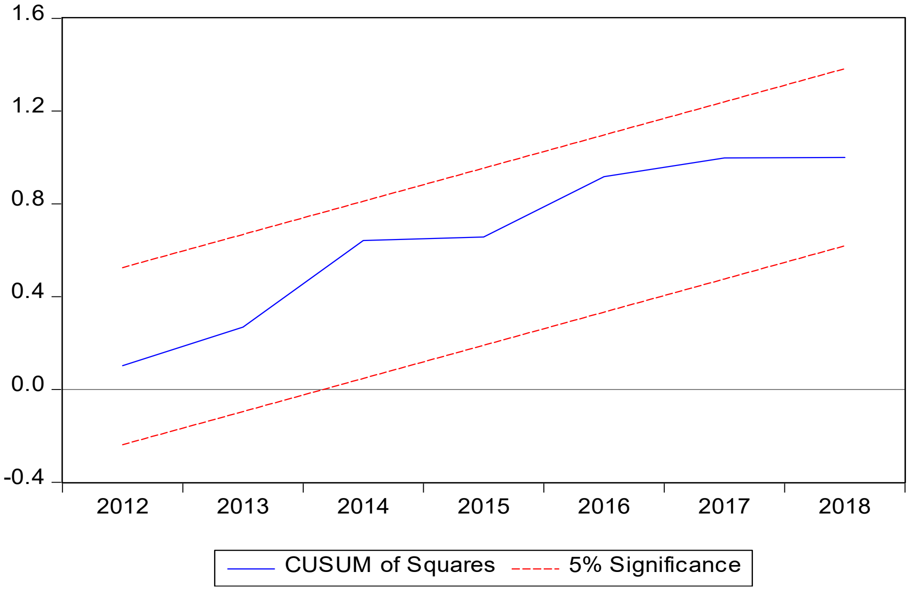

Figure 5. Plot of cumulative sum of squares of recursive residuals. (Source: Authors' calculations).

4.4. The VECM Granger Causality Tests

As CO_2 emissions, energy consumption, population density, economic growth, and exports in China are cointegrated (see Section 4.2), we undertook the VECM Granger causality tests [83] to investigate the direction of causal relationships between these variables.

The findings shown in Table 6 indicate that short-run unidirectional Granger causality exists from economic growth to CO_2 emissions, energy consumption, and exports. In addition, short-run causal relationships are found from CO_2 emissions to energy consumption and exports. In regard to long-run causality amongst the selected variables, the coefficients of ECM_{t-1} in CO_2 emissions and exports are significant at 5% and 1%, respectively (Table 6).

These findings provide evidence of long-run bidirectional causality relationships between CO_2 emissions and exports.

Table 6. The results of VECM Granger Causality approach.

Dependent Variable	Short-Run Causality Independent Variable						Long-Run ECM_{t-1}
	ΔLnC	**ΔLnE**	**ΔLnG**	**ΔLnG^2**	**ΔLnP**	**ΔLnX**	
ΔLnC	-	−0.4393 (−0.7889)	−5.4846 ** (−2.2121)	0.4246 ** (2.1049)	1.4035 (1.0583)	−0.0612 (−0.9395)	−1.0986 ** (−2.4085)
ΔLnE	0.8030 ** (2.5502)	-	−3.8249 ** (−2.0688)	0.2777 (1.8465)	5.3682 (0.5428)	−0.0256 (−0.5283)	0.2178 (0.4678)
ΔLnG	−0.0062 (−0.0225)	−0.1745 (−0.4776)	-	0.1969 (1.4871)	1.2993 (1.4927)	−0.0606 (−1.4164)	−1.1900 (−1.7248)
ΔLnG^2	0.8923 (0.2548)	−3.3126 (−0.7172)	−2.8484 (−1.3854)	-	1.4364 (1.3061)	−0.7280 (−1.3461)	0.5974 1.0656)
ΔLnP	0.0094 (1.3991)	−0.0111 (−1.2538)	0.0143 (0.3625)	−0.0012 (−0.3808)	-	0.0009 (0.8651)	−0.0101 (−0.8426)
ΔLnX	2.8186 ** (2.1597)	−3.4933 (−2.0296)	−2.2707 *** (−2.9634)	1.7325 *** (2.7788)	4.9995 (1.2197)	-	−1.0285 *** (−4.2557)

Note: *** and ** indicate significant at 1% and 5%, respectively. (Source: Authors' calculations).

5. Conclusions and Policy Implications

This paper explores the main factors for environmental degradation in China, and whether the environmental Kuznets curve hypothesis holds in the country over the period of 1971–2018. We apply the unit root tests for the stationarity analyses of selected variables, and the ARDL bounds tests for the long-run links among the variables. The causal relationships amongst CO_2 emissions, energy consumption, economic growth, population density, and exports are explored by the VECM Granger causality approach. The obtained results demonstrate that the selected variables are cointegrated. In addition, the energy consumption and economic growth (real GDP) found are the major factors for CO_2 emissions in both the short-run and the long-run. In contrast, exports decrease CO_2 emissions in the long run. The results also show that the environmental Kuznets curve held in China during the study period of 1971–2018. The results of the VECM causality tests provide evidence of short-run unidirectional Granger causality running from economic growth to CO_2 emissions, energy consumption, and exports, as well as from CO_2 emissions to energy consumption and exports. Moreover, the long-run causal links are found between CO_2 emissions and exports.

Based on our empirical results, the following policy recommendations are worth noting: Firstly, China's economic growth rate over the last decades is remarkable, which has resulted in high energy consumption, as well as environmental degradation. However, this growth rate will not be sustainable in the long term while maintaining the desired environmental quality. Therefore, China should set a policy target for a reasonable economic growth rate each year, and emphasize the quality rather than the quantity of economic growth. China should limit very high growth aspirations through production which demands excessive use of nonrenewable energy that ultimately increases CO_2 emissions. Even if the current annual economic growth rate and energy consumption levels are considered desirable for the sake of the economy, China should explore more green energy sources which are environmentally friendly. Although China's COVID-19 responses comprise elements of a green recovery, and the Chinese government has announced more comprehensive stimulus packages towards a digital economy [99], the effective implementation of the policies is critical.

Secondly, more imports of energy efficient technologies for domestic production, along with the national carbon credit trading market, should take place sooner to reduce CO_2

emissions. In 2017, the Chinese government piloted the emissions trading scheme that incentivizes companies in five cities within Hubei and Guangdong to cut emissions by putting a "price" on CO_2 [100]. The pilot achieved some success, with approximately 38 million tons of CO_2 traded in regional carbon markets. Although the trading scheme officially in early 2021 [101], the successful implementation of the scheme across the country is important.

Thirdly, the government should encourage and provide incentives for greater use of renewable energy to mitigate CO_2 emissions, as well as environmental damage. More than 300 million motor vehicles use less energy efficient engines on the roads in China; they are major sources of CO_2 emissions [101]. The government needs to continue the limits on fuel consumption for new motorcycles and mopeds, and suspend car models that do not meet strict fuel standards. The government also needs to further implement incentives to encourage the transition to electric vehicles.

Fourthly, all sectors, industries, and people in China should be further educated through campaigns, advertisements, and training in order to encourage them to change their behavior and require responsibility for environmental protection, as noted by the 2007 Chinese Communist Party Congress. The Chinese government should further cultivate public support for energy conservation and environmental awareness [101].

Finally, rather than focusing on separate individual sectoral policies, a combined policy for sustainable economic growth, energy consumption, environmental protection, and optimum trade, through public and private partnership and initiatives, might be more fruitful. Therefore, future research should be directed to: (i) determine the desired economic growth rate for the short-run, medium, and long-run; (ii) set the target for annual CO_2 emissions level; (iii) set the increased proportion of renewable energy consumption compared to nonrenewable energy; and (iv) find out the optimum production, consumption, and trade volume.

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Abbreviations

AIC	Akaike information criterion
ARDL	Autoregressive Distributed Lag
CUSUM	Cumulative sum of recursive residuals
CUSUMSQ	Cumulative sum of squares of recursive residuals
EKC	Environmental Kuznets Curve
GDP	Gross Domestic Product
ECM	Lagged error term
UN	United Nations
VECM	Vector Error Correction Model
WTO	World Trade Organisation
C_t	CO_2 emissions per capita,
E_t	Energy consumption per capita

G_t (G_t^2)	Real GDP (squared) per capita
P_t	Population density
X_t	Export per capita
μ_t	Error term

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