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Pathway to achieving carbon goal: Insight from interaction of export diversification, renewable energy, innovation, and financial policy

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Abstract

Even though China has mapped out different policies targeting the mitigation of its environmental degradation, the country still occupies the 1st position in the ranking of carbon emissions due to excessive utilization of non-renewable energy sources in its domestic economic activities. From a theoretical and empirical point of view, factors like economic growth, financial development, export diversification, technological innovation, and renewable energy can be considered to play a vital role in environmental quality. Therefore, this study exposes the environmental performance of China amidst export diversification, financial development, innovation, and clean energy use. Due to the non-availability of data, the annual data of China are converted to quarterly data from 1995Q1 to 2018Q4, and autoregressive distributed lag-(ARDL) and Granger causality approaches are adopted in this study for quantitative and insightful analysis. The findings from both approaches expose the environmental implications of the selected variables (renewable energy, financial development, technological innovation, and export diversification) to China's sustainable development. ARDL approach has confirmed the inverted U-shaped link between financial development and emissions of carbon for China, a negative link between renewables, technologies, and carbon emissions, and a direct association exists between the diversification of export, economic growth, and emissions of carbon. This pattern points toward mitigating environmental dilapidation with renewable energy, technology, and financial development. The Granger causality output lends support to the ARDL findings; hence, a policy initiative that will promote the renewable energy sector and technological innovation through financial programs is advised.

Keywords Environmental quality · Carbon neutrality · Export diversification · Financial development · Renewable energy · Technological innovation · China

JEL Classification C22 · O31 · O53 · Q20 · Q53

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1 Introduction

Globally, greenhouse gas (GHG) emissions (mostly carbon dioxide and methane) have increased dramatically over the last century due to increased energy demands and technological advancements that have impacted human life (George et al., 2021). The majority of current energy need is achieved by burning non-renewables, which create large amounts of greenhouse gases (GHG), leading significantly to global warming and temperature rise, as well as a large carbon footprint and several severe environmental effects. In 2019, China's GHG emissions surpassed that of the USA and other developed countries (CNBC, 2021). A recent report shows that China accounts for more than a quarter of all global emissions; the USA is the world's second-largest emitter, contributing 11% of worldwide emissions, India is responsible for 6.6 percent of global emissions, and the 27-member states of the European Union (EU) are responsible for 6.4 percent. According to Rhodium assessments, China's net emissions grew by 1.7 percent in 2020 even though emissions from practically all other countries decreased during the coronavirus outbreak.

The growing demand for energy improvements around the world results in economic growth and technological advancement. Although energy consumption can lead to economic progress, it is the principal source of environmental degradation (Philip et al. 2021). As a result of these problems, the production of new technologies to drastically reduce carbon emissions has gained great attention, with significant progress made in recent years. President Xi Jinping of China is committed to lowering carbon emissions at the national level by enacting stronger laws and policies, attaining a peak in carbon dioxide emissions by 2030, and attempting to achieve carbon neutrality by 2060. Furthermore, CO2 emissions, which are especially tied to energy, are expected to rise by 2030, according to Chinese officials. As a result, it would be expedient to evaluate energy consumption with the factors that influence CO2 emission changes to comprehend energy efficiency and mitigate GHG emissions to attain a low-carbon economy. The role of trade, on the other hand, is to promote environmentally friendly technology and regulate industrial GHG discharges to emissions and mitigate the consequences of climate change. This is because trade has the potential to cut GHG emissions indirectly through technological benefits. Additionally, trade openness has an impact on the quality of the financial sector, which has a direct and indirect impact on economic growth (Pradhan et al., 2017).

Financial development enhances savings growth, technical development, and the ability to reduce GHG emissions as a result of economic growth (Sadorsky, 2011; Shahbaz et al., 2013a). Financial development is the key to enhancing energy innovation, which improves energy efficiency and, as a result, can help to reduce environmental pollution. Many scholars have looked into the relationship between financial development and environmental degradation, with varying results. A positive relationship between financial development and environmental quality was found by Kirikkaleli and Adebayo (2021); Baloch et al. (2021); Tamazian et al. (2009). In contrast, a negative correlation is documented in Zhang (2011). Furthermore, other studies uncover an inverted-U relationship between financial development and carbon emissions, indicating that while financial development initially increases CO2 emissions, this reduces as the financial sector grows (Shahbaz et al., 2013a; b, c). The EKC linking income expansion and releases of carbon was validated in the majority of investigations, indicating that economic expansion is first associated with an increase in CO2 emissions before decreasing as the country develops (Ozturk & Acaravci, 2010).

Against this backdrop, the goal of this research is to look into the consequences of financial development, renewable energy, as well as technological innovation, and trade to achieve long-term environmental quality in China. The growing economy of China is recognized as one of the worst-affected economies due to the increasing level of GHG emissions. China's economic growth is partly trade oriented that is centered on heavy industrial and manufacturing activities, and these activities are based on excessive utilization of non-renewable sources. The whole process is capable of impacting environmental development negatively through the excessive carbon emissions from the use of non-renewable resources. Also, following the increasing arguments that support the effectiveness of financial development in cushioning the effect of pollution on the environment through technological innovation and research expansion, the present study employs the novel financial EKC to examine the success level of financial policy in correcting environmental dilapidation on China's environment. On this premise, the present study attempts to investigate the best policy for achieving sustainable environmental development for China by applying financial policy, renewable energy policy, and technological innovation policy with trade to test the possibility of achieving a carbon–neutral goal for China. Export trade diversification is considered a trade indicator and the present study quantifies export exportation with the adoption of financial EKC to ascertain the objective of the study. In light of this, we attempt to find the most effective way of recovering China's development from the impact of GHG emissions. For a better understanding of the goal, as mentioned, we use financial development (private sector financing), renewable energy, trade, and technical innovation (R&D) to assess China's environmental performance. Our investigation will focus on the following areas: (a) Is China's financial development policy part of the country's efforts to improve and restore its environmental quality? (b) Can renewable energy help China achieve a more sustainable environment? (c) Does technological innovation policy contribute to environmental sustainability? (d) Will trade activities be able to contribute to environmental sustainability? The results of the estimation and analysis will address the above-mentioned issues in connection to GHG emissions and also whether the policies will help China to achieve long-term environmental sustainability.

Following the objectives of this study as enshrined in the above-highlighted questions, we propose incorporating the squared term of financial development into the EKC hypothesis equation to determine whether the nonlinear link between financial development and GHG emissions is inverted U-shaped or not. Using autoregressive distributed lag (ARDL) technique, we investigate the policy implications of financial development, energy efficiency, technical innovation, and trade on China's environmental sustainability. This study will contribute to the literature by applying and expanding the financial policy with the EKC theory. Many studies have focused on economic growth and EKC with less focus on applying the EKC hypothesis to finance policy. By applying and expanding the EKC hypothesis of finance instead of the popular growth-EKC nexus, the present study contributes to the literature. Also, the present study adopts and quantifies trade in the dimension of export diversification to expose the environmental implication of export diversification in the case of China. This will also contribute to the economy–energy–environmental research literature. By identifying the environmental implication of the selected variables, our study adds to the sustainable development of China. Overall, this empirical study will contribute to environmental sustainability, and provide policymakers and government officials with specific policy recommendations to gain a better understanding of how to address the challenges posed by GHG emissions. The findings and policies suggested in our study will be of great relevance and implication to other emerging and neighboring countries in the pursuit of their environmental and sustainable goals.

The rest of this paper is organized as follows: The previous studies are summarized in Sect. 2. Section 3 covers data, econometric modeling, and estimation methods. Section 4 presents empirical results and discussion. Section 5 contains conclusions and policy recommendation.

2 Literature review

The chosen topic has been researched by some scholars with different scientific approaches and variables but with varied findings and conclusions. The research attempts have taken different approaches concerning country or country perspectives. Due to the inconclusive nature of the findings and conclusion, and equally the evolving pattern of the climate issue which calls for a solution to the existential problem, the research topic has to remain open and calls for different approaches toward the solution. A review of some scholarly works with different variables and approaches is presented under different subsections with the chosen variables in this study as follows: Financial development was applied in the work of Charfeddine and Khediri (2016) as a tool in improving UAE's environment. Their study adopted regime-switching cointegration techniques with the application of a Quadratic EKC pattern of financial development to unveil the impact of finance and other instruments on the UAE's environment. One of their findings was an inverted U-shaped relationship between economic growth, financial development, and carbon emissions. Apart from the above-mentioned work, other scholars (Shahbaz et al., 2013a, 2013b, 2015; Tamazian and Rao, 2009, 2010; Jalil & Feridun, 2011; Zhang, 2011; Al-mulali & Sab, 2012; Boutabba, 2014; Ozturk & Acaravci, 2013 and Rahman & Alam, 2022b) have tested the impact of financial development on the environment. The findings from the stated studies are disaggregated with mixed (positive and negative) results which leave space for additional scientific research into the impact of financial development on environmental development. Hence, scholars like Tamazian et al. (2009), Tamazian and Rao (2010), Jalil and Feridun (2011), Shahbaz et al. (2013a, b, 2015), Rahman and Alam (2022b) for Malaysia, Indonesia, South Africa, and Australia found financial development as a degrading factor on the environmental quality, while other scholars like Zhang (2011), Al-mulali and Sab (2012), Boutabba (2014) and Ozturk and Acaravci (2013) found financial development impacting favorably to the environment development.

Export diversification index and economic growth (GDP per capita) have been utilized by some other scholars in analyzing the measures of improving the environment through carbon moderation. The instruments and approaches of export diversification FMOLS (fully modified ordinary least squares), dynamic ordinary least squares (DOLS), and ARDL, and to study the environmental performance of 84 developing countries. Part of the findings is a positive association between outward trade expansion and pollution release, while Liu et al. (2018) applied the instrument of export diversification to study the environment of Korea, Japan, and China. The study found the link between export diversification and ecological footprint to be positive in the case of China, Korea, and Japan. Shahbaz et al. (2019) applied bootstrapping ARDL and VECM to investigate the impact of export diversification for the USA; the study found a negative relationship between export diversification and energy demand. Bashir et al. (2020) applied panel quantile regressions and the system Generalized Method of Moments (GMM) with the instrument of export diversification to study the environmental performance of 29 OECD countries; the study found diversification mitigating carbon release.

Also, Saboori et al. (2022) applied ARDL with FMOLS and DOLS to investigate the impact of export diversification on Oman's environmental development; they found a positive impact of export diversification on the country's environmental degradation.

Further in this review, we present other studies that have experimented with technology and renewable energy toward improving the environment. Scholars (Aghion et al., 2016; Yu et al., 2020 and Nassiry, 2018) have investigated environmental development through technological innovation and green technology innovation. The study by Mensah et al. (2018) on 28 OECD countries showed that carbon emission was reduced by technological innovation. Also, a study by Wurlod and Noailly (2018) on 17 OECD countries suggests that green innovation reduced carbon emissions through a cut in energy intensity. The same result was found in the work of Alvarez-Herranz et al. (2017) on 28 OECD countries where innovation seems reducing carbon emissions. The clean energy mitigates emissions of carbon in the case of European Union nations. The study by Yu et al., (2020) suggested that renewable energy sources reduced carbon emissions in the case of Nordic countries. Also, the study by Liu et al. (2022) confirmed the ability of technological innovation and renewable energy in improving the quality of the environment through carbon mitigation. Rahman and Alam (2021) investigated the environmental performance of Bangladesh and found clean energy mitigated carbon emissions in the country. Rahman and Alam (2022a) also found that financing, international trade, and economic expansion are detrimental to the atmosphere quality for 17 Asia–Pacific nations. Udemba and Tosun (2022) in their study, found that renewable energy mitigated environmental dilapidation in Brazil. Udemba et al. (2022) adopted a dual approach of symmetric and asymmetric to study the environmental performance of Malaysia; the study found both renewable energy and technology mitigating environmental degradation. Sultana et al. (2022) and Rahman and Alam (2022b) equally found renewable energy mitigating environmental dilapidation in Bangladesh and Australia, respectively. Bekun (2022) applied CCR, FMOLS, and DOLS to evaluate the impact of clean energy and economic growth in the power sector on CO_2 emissions in the India in the long run. They discovered that India's substantial use of clean energy lower emissions of CO2. Bekun et al. (2022) in a study of E7 economies, revealed renewables are viewed as an effective way to minimize pollution emissions. Adedoyin et al. (2021) concluded that increase energy use, real GDP per person, and tourism contribute to rising carbon emissions in the four EU macro regions'.

Also, scholars (Udemba & Alola, 2022; Udemba, 2022; Rahman & Vu, 2021 and Ekwueme et al., 2022) have written and compared the economic growth with the environmental performance of many countries. Hence, Udemba and Alola (2022) applied the asymmetric method to research Australian environmental performance with its economic performance; the study found economic growth increases pollution release in Australia. Udemba (2022) in a study of Turkish environmental performance, revealed economic growth increases the carbon emission thereby hampering the environmental development of the country. Rahman and Vu (2021) in their study on China's environmental performance, found economic growth induces environmental dilapidation. Also, Ekwueme et al. (2022) demonstrated economic growth enhances CO2 emissions in Asian nations including China. Bekun et al. (2022) examined the connection among the growth of leisure industry and the income expansion for emerging industrialized nations (E7) in the long run; they discovered that a surge in fossils and income per capita leads to higher CO2 emission in E7 nations. Caglar et al. (2022) established that improvements in liberalized trade and income complications promote eco-friendly in the BRICS economies.

3 Data, models, and econometric approaches

3.1 Data and variable

The study was carried out using quarterly data of China from the 2022 WDI (World Bank Development Indicators), beginning at 1995Q1-2018Q4. For this study, the following variables were utilized: greenhouse gas emissions per capita, financial development, export diversification index, renewable energy, technological innovation, and GDP per capita (economic growth). Technological innovation is measured as residents' patent rights. Renewable energy is measured by total renewable energy. Financial development is measured as (domestic credit to the private sector by bank % of GDP). Economic growth is measured by GDP per capita (constant, 2015 US). Environmental sustainability is measured by greenhouse gas emissions per capita. The export diversification index is measured by Merchandise: Concentration and diversification indices of exports by country. The variables and their symbols are summarized in Table 1.

3.2 Model specification

Theoretically, the study was modeled on EKC (Environmentally Kuznets Curve) hypothesis. Numerous studies (like Shahbaz et al., 2015, and Ekwueme et al. (2022)) have modeled their research based on the EKC hypothesis following the seminal papers of Grossman and Krueger (1995) by addition of more variables to the fundamental equation of EKC. Our explanatory variables include clean energy, financial development, export diversification index, and technological innovation in addition to GDP per capita. Financial development could be proxied by either the stock market series or banking indicators. Nevertheless, because of the availability of the data and that stock market indicators' time series are scanty, we utilized the banking variable—the ratio of domestic credit to the private sector (% of GDP), which is the most common banking variable used to measure financial development. To check if the nonlinearity association between financial development and emissions of the greenhouse is an inverted U-shape or not, we include the financial development squared term ($FINDEV^2$). According to Shahbaz et al. (2016), at the initial phase of economic growth, the financial sector does not bother much about the environment; however, the financial sector enhances environmental quality at the maturity phase by leasing loans to green projects. Shahbaz et al. (2013a; b, c,) confirmed that an inverted U-shaped association exists between financing and the deterioration of the environment in Indonesia.

Table 1 Data and variable summary Source: Authors' compilation

Variables	Symbols	Measurements	Sources
Renewable energy	TRE	Total renewable energy	World Bank Data
Export diversification index	EXPDIVIN	Diversification indices of exports by country	World Bank Data
Financial development	FD	Domestic credit to the private sector by a bank (% of GDP)	World Bank Data
Green House gas emissions	GHGMPC1	Green House Gas emissions per capita	World Bank Data
Technological innovation	PATENT	Patent rights (residents)	World Bank Data
Economic growth	GDPPC	GDP per capita (constant, 2015 US$)	World Bank Data

Thus, following Shahbaz et al. (2016), Ekwueme and Zoaka (2020), and Shahbaz et al. (2013a; b, c), the model for this study is expressed as follows:

$$GHGMPC1_t = \alpha_1 EXPDIVIN_t + \alpha_2 FINDEV_t + \alpha_3 TRE_t + \alpha_4 GDPPC_t + \alpha_5 \mathrm{PATENT} + \varepsilon_{it} \tag{1}$$

Further, to ascertain inverted EKC linkages exist between finance and the environment in China, we have extended the model to include a square term of financial development. Thus, Eq. (1) is transformed as follows:

$$GHGMPC1_t = \alpha_1 EXPDIVIN_t + \alpha_2 FINDEV_t + \alpha_3 FINDEV_t^2 + \alpha_4 TRE_t + \alpha_5\ GDPPC_t + \alpha_6 PATENT_t + \varepsilon_{it} \tag{2}$$

where $GHGMPC1_t$ = Greenhouse gas emissions per capita ,$GDPPC_t$ = economic growth, $EXPDIVIN_t$= Export diversification index, $PATENT_t$ = technological innovation, $FINDEV_t$= financial development, TRE_t = Total renewable energy, $FINDEV_t^2$ = square term of financial development, and ε_{it}=error term. α_1, α_2, α_3, α_4, α_5, and α_6= the estimated parameters.

3.3 Econometrics approach

The study employed augmented Dicker–Fuller (ADF) and Philip–Perron unit root tests to ascertain if the variables are stationary. The unit root analysis is essential to know if the series are integrated in order of 1, which is the prerequisite for estimating the long-run relationship between the variables. Secondly, the study utilized the Pesaran et al. (2001) ARDL Bound cointegration test to test for cointegration among the variables. We utilized this approach because its application is dynamic notwithstanding the order in which the series are integrated of. It is useful as it conducts a double investigation by computing first the short-period and long-period linkages among the series and subsequently examining the causality between the series. F-stat of Pesaran et al. (2001) were employed in the determination of the presence of long-run association among variables. The decision rule is to reject the null hypothesis if the F values are more than the upper bound critical values and vice versa.

Subsequently, the study used the autoregressive distributed lag (ARDL) model to investigate the dynamic association between the explanatory variables and the explained variables. The study utilized this econometric approach because its application is dynamic notwithstanding the nature of the cointegration among the variables.

Finally, the Block Exogeneity Wald/VAR Granger test of causality evolved by Enger and Granger (1987) was used to assess the direction of Granger causality between the variables.

4 Empirical results and discussion

4.1 Graphical display of the variables

4.2 Descriptive statistics

The estimated outputs of the descriptive statistics are displayed in Table 2.

Table 2 Descriptive statistics Source: Authors' computation with EViews

	GHGMPC1	FIN_DEV	GDPPC	EXP.DIV.IN	PATENT	TRE
Mean	0.005643	120.5619	4642.348	0.453113	359,875.3	147.8329
Median	0.005764	117.9404	4059.891	0.458973	137,689.0	106.5715
Maximum	0.008871	157.8091	9619.192	0.477520	1,393,815	372.1845
Minimum	0.000000	83.09731	1520.027	0.410134	10,011.00	44.92045
Std. Dev	0.002659	20.78320	2613.062	0.019420	447,643.8	105.3946
Skewness	− 0.439625	0.313636	0.470277	− 1.319806	1.161062	0.790021
Kurtosis	2.351433	2.385336	1.865593	3.527797	2.929971	2.292753
Jarque–Bera	1.293197	0.771282	2.171522	7.246126	5.397164	2.996730
Probability	0.523825	0.680015	0.337645	0.026701	0.067301	0.223495

The descriptive statistics outcome reveals that there is a large fluctuation between financial development, renewable energy (TRE), export diversification index, GDP per capita (GDPPC), Patent, and greenhouse gas emissions per capita (GHGMPC). The Jarque–Bera outcome shows that the majority of the series is distributed. Thus, for this study, the use of asymmetric estimations based on descriptive statistics is vital.

4.3 Unit root test outputs

Before estimating data that are time-series, it is important to ascertain the series' non-stationarity. The study employed the Philip–Perron (PP) unit root test and augmented the Dickey–Fuller-DF test to establish the stationarity of the series. The output of both unit root tests is displayed in Table 3.

The two-unit root test outcome in Table 3 reveals that the entire series is integrated in order of 1(1).

4.4 Cointegration test

The F-statistics from the Pesaran et al. (2001) ARDL bound test cointegration test was utilized in the determination of whether cointegration exists among the indicators, and the outcome of the cointegration test is shown in Table 4.

In Table 4, the null hypothesis of no long-run association between the series is rejected since the F-statistics (5.67) of the Pesaran et al. (2001) bound test is larger than the critical value (3.99) at a 0.01% significance level. Therefore, we concluded that there is strong evidence of cointegration among the variables. This suggests that financialization, export diversification, and patent are essential to the environmental sustainability of China.

4.5 Estimated results of the autoregressive distributed lag (ARDL) model

The ARDL estimation (long-run and short-run) outputs are displayed in Table 5. The coefficients of some of the variables are the same in both periods; the differences lie in the standard error and the statistic. The R^2 (0.95%) which is the goodness of fit implies that the explanatory variables (financial development, export diversification index, economic

Table 3 PP and ADF unit root outputs Source: Authors' computation

Variable	Level			1st Diff			Remarks
	Const	Const./trend	Without Const./trend	Const	Const./trend	Without Const./trend	
PP							
GHGMPC1	– 1.322	– 0.307	– 0.814	– 4.689**	– 5.164**	– 4.763**	I(1)
FINDEV	– 0.869	– 1762	– 2.163	– 3.898**	– 3.776**	– 3.413**	I(1)
GDPPC	5.033	– 1.906	11.644	– 0.362	– 2.130**	1.884	I(1)
EXPDIVN	– 0.759	– 1.544	– 1.322	– 2.796*	– 2.627	– 2.754**	I(1)
PATENT	4.848	0.601	6.988	– 1.726	– 4.581**	– 0.734	I(1)
TRE	4.818	– 0.365	9.272	– 4.208**	– 14.10**	– 2.033**	I(1)
ADF							
GHGMPC1	– 1.196	0.997	– 0.814	– 4.689**	– 5.164**	– 4.763**	I(1)
FINDEV	– 0.810	– 1.762	2.122	– 3.954*	– 3.855**	– 3.450**	I(1)
GDPPC	0.924	– 2.307	0.816	– .0.759	– 2.115	1.320	MIXED
EXPDIVN	– 1.544	– 2.876	– 1.319	– 3.740**	– 3.900**	– 3.434**	I(1)
PATENT	– 1.618	– 1.619	– 3.892**	0.203	– 1.689	1.476	MIXED
TRE	4.692	– 0.261	6.632	– 1.275	– 9.254**		

ADF augmented Dickey–Fuller*, PP* Philips–Perron. Note: * and ** significant levels at 10% and 5%

Table 4 Output of the ARDL bound cointegration test Source: Authors' computation

Test Statistic	Value	Signif	I(0)	I(1)
F-bound test				
F-statistic	5.670	10%	1.99	2.94
K	6	5%	2.27	3.28
		2.5%	2.55	3.61
		1%	2.88	3.99

growth, technological innovation proxy by patent, and total renewable energy) account for 95% of variations in the dependent variable (greenhouse gas per capita).

The ARDL estimation outputs in Table 5 show that EXPDIVIN (export diversification index) and economic growth (GDPPC) influence on the GHG per capita of China in both periods is positive. The historical economic positive economic performance of China is traced to highly industrial and manufacturing activities that are centered on the high utilization of fossil fuels. China is on the top list of exporting countries following its success story in industrial and manufacturing processes. The process that leads to China standing tall in export competition is centered on the high utilization of fossil fuels which transcends to an increase in GHG. This will translate into poor environmental performance. Therefore, the progressive connection among the economic growth, outward trade expansion, and greenhouse gas releases is not far from the reality of the economic situation of China. Empirically, this implies that increasing the export diversification index by one unit will amount to 0.001 and 0.024 GHG per capita of China in both periods. Also, a unit surge in economic growth will increase the GHG per capita of China by 1.41 in both periods. For the case of export diversification, our finding aligns with, Liu et al. (2018), and Saboori

Table 5 Estimation output of ARDL model (dependent variable = GHGMPC1) Source: Authors' computation with EViews

Variables	Coef	S.Error	t-stat	Prob
Long run				
FINDEV	1.11	1.08	1.029	0.306
FINDEV^2	− 5.92	4.53	− 1.307	0.194
EXPDIVIN	0.001***	0.0003	3.628	0.000
GDPPC	1.41***	2.37	5.945	0.000
PATENT	− 2.63***	5.54	− 4.742	0.000
TRE	− 4.46***	8.34	− 5.34	0.000
C	− 0.003	0.003	− 0.908	0.366
Short run				
FINDEV	1.11*	6.20	1.790	0.077
FINDEV^2	− 5.92**	2.67	− 2.219	0.029
EXPDIVIN	0.024***	0.004	5.080	0.000
GDPPC	1.41***	2.04	6.908	0.000
PATENT	− 5.84***	1.39	− 4.742	0.000
TRE	− 4.46***	8.34	− 5.34	0.000
ECT	− 0.04***	0.006	− 7.038	0.000
Diagnostics tests				
R^2	0.95			
Adj. R^2	0.95			
F-stat	1744 (0.000)			
DW statistics	2.05			
R^2	0.95			
χ^2 *LM*	0.0839 [0.7727]			
$\chi 2$ *HET*	0.0895 [0.1007]			

*,** and *** denote 10%, 5%. and 1% Prob. stand for probability which represents *P* Value

et al. (2022) research outputs who found a positive link between export diversification and GHG for 84 developing countries, Korea, Japan, and China, and Oman, respectively. However, outputs from Shahbaz et al. (2019) and Bashir et al. (2020) regarding the negative link between GHG and export diversification for the case of the USA and 29 OECD countries contradict our findings. This is expected considering the economic advancement of the countries involved in the studies. The ones with a positive pattern of the link between GHG and export are the developing or emerging countries, while the countries with a negative link are the advanced or developed countries. Advanced countries are more sensitive to the impact of economic performance on the environment and, hence, tend to mitigate environmental degradation with strong policies. However, the reverse is the case for developing countries which tend to focus more on achieving growth than environmental development. On the growth finding, our finding supports the findings from Udemba et al. (2022), Udemba (2022), Rahman and Vu (2021) and Ekwueme et al., (2022) who find that increase in economic growth enhances emissions of carbon in Asian countries including China.

On the contrary, technological innovation (patent) and total renewable energy (TRE) have a significant negative linkage with the GHG per capita of China in the short and long run. Arguments from some studies are in favor of the ability of technological innovation and renewable energy in curtailing the emission rate due to a diversification policy that is guaranteed by a shift from fossil to clean sources of energy. Technological innovation is one way of achieving this shift which entails developing new methods of achieving same result with lesser use of fossil fuels. The era of the industrial revolution suggests excessive use of fossil fuels because the early machines are manufactured to be run by fossil fuels. The adoption of new technologies suggests shifting from old ways to new ways with new technologies. This implies that a unit increase in technological innovation (patent) would decrease the GHG per capita of China by 2.63 and 5.84 in both periods accordingly. Also, in both periods, a unit surge in total renewable energy would decrease the GHG per capita of China by 4.46. The output proves that the rise in clean energy and technological innovation in China is a vital tool in determining the environmental sustainability of China. These findings are in support of the findings of Rahman and Alam (2021) for the case of renewable energy, Udemba et al. (2022) for renewable energy, Udemba and et al. (2022) for renewable and technology and Ekwueme et al. (2022) who found that increase in renewable energy mitigates emissions of carbon in Asian countries including China.

Regarding FINDEV (financial development), the output in Table 5 reveals that at the initial stage of financial development of China, a positive link between financial development and GHG per capita is established in both the long run and short run, notwithstanding the impact is insignificant in the long run. This finding supports a positive argument for financing environmental sustainability. Financial development enhances energy diversification leading to the development of clean energies through new technologies due to technological innovation. This will assure environmental sustainability. This implies a unit increase in financial development will increase the GHG of China by 1.11in the short run. Contrarily, the coefficient of the square of financial development ($FINDEV^2$) has a negative sign in both periods. However, the coefficient for long-run period is insignificant. This implies that the turning point of the link between financial development and GHG displayed a negative pattern. This means that increasing the financial development squared by a unit in the short run would lead to a decrease in the GHG emissions of China by 5.92. Additionally, the output supports the inverted U-shape EKC hypothesis for China by having a positive sign for financial development and a negative sign for financial development squared (Ekwueme and Zoaka 2020, Kwakwa & Adu, 2016). The output is insightful for policymakers in China on the need to enact policy that will shape the financial sector to nuance the standards of the environment by offering loans that encourage investment in eco-friendly projects. This will enhance the quality of life and the environment by increasing the efficiency of all sectors and mitigating GHG emissions. This pattern is equally established in the works of Charfeddine and Khediri (2016), Zhang (2011), Al-mulali and Sab (2012), Boutabba (2014), and Ozturk and Acaravci (2013). However, in support of the findings from the short run of the initial stage, scholars like Tamazian et al. (2009), Tamazian and Rao (2010), Jalil and Feridun (2011), Shahbaz et al. (2013a, b, 2015), for Malaysia, Indonesia, South Africa found financial development as a degrading factor on the environmental quality.

The ECT (0.04) has a negative sign and is statistically significant, and this implies that the model will adjust to any disequilibrium in the short run by 4%. This indicates that for the Chinese economy, the speed of adjustment to any shock in the GHG emissions models is very slow. Further, the ECT results vide additional support to the ARDL bound cointegration test output of the existence of a long-period association among the sampled series. The graphical representation of the series are presented in Fig. 1 below.

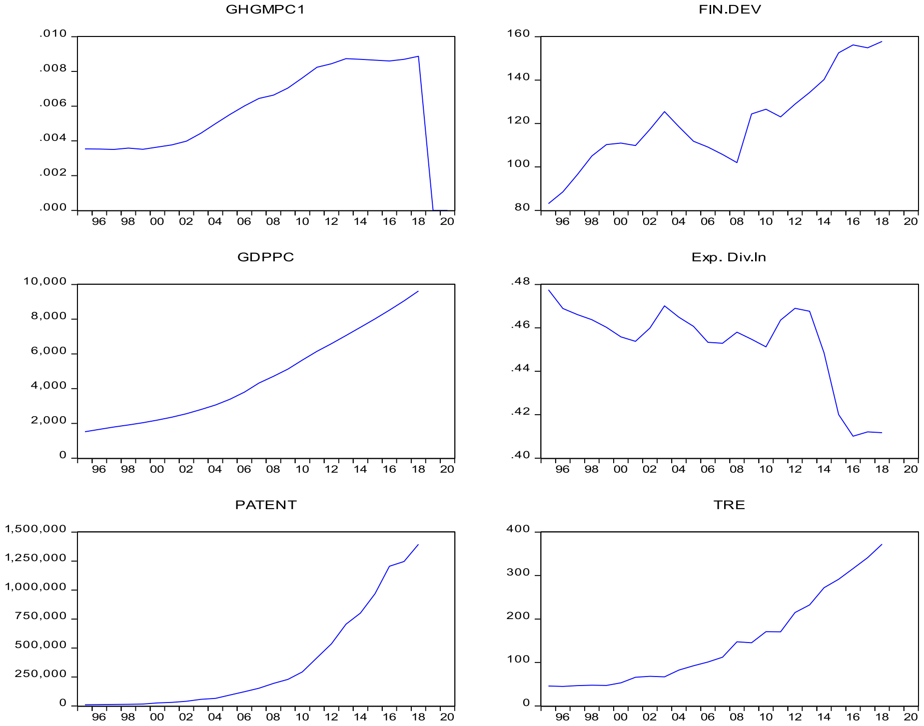

Fig. 1 Graphs of the sampled variables. Source: author's computation

4.6 Diagnostic tests

The output of the diagnostics tests is presented in Table 5. The heteroscedasticity was ascertained using the Breusch–Pagan–Godfrey test 0.0895 [0.1007]; the serial correlation was ascertained using the Breusch–Godfrey serial correlation LM test 0.0839 [0.7727], and the multicollinearity was tested using the Durbin Watson (2.05). The estimation results of these diagnostics tests suggest that our model is free from heteroscedasticity and serial correlation. Further, CUSUM and CUSUM^2 diagnostic tests were also estimated in this study to test the model's stability and the outputs are displayed in Figs. 2 and 3, respectively. The output in Figs. 2 and 3 reveals that the blue lines are in between the two red lines; this shows that the model is stable.

4.7 Estimation of VAR Granger causality/block exogeneity Wald tests

The VAR Granger Causality/Block Exogeneity Wald tests in Tables 6 and 7 were used by this study to supplement and check the robustness of the ARDL output in Table 5. The long-run VAR Granger Causality/Block Exogeneity Wald tests in Table 6 revealed a two-way Granger connection between financial development, renewables, and GHG emissions in the long run. This output is in support of Shahbaz et al. (2013a; b, c) and Ekwueme et al. (2021) who found financial development Granger-cause emissions of CO_2 in Malaysian

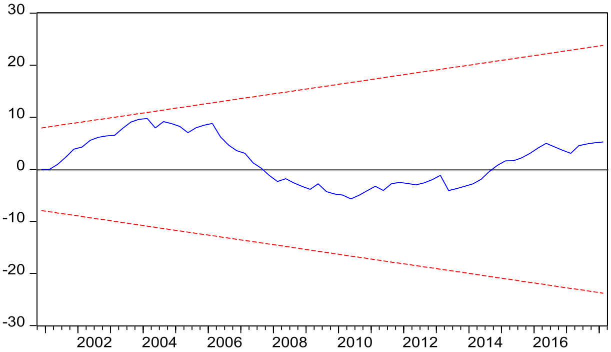

Fig. 2 Plot of cumulative sum (CUSUM). Source: Authors' computation

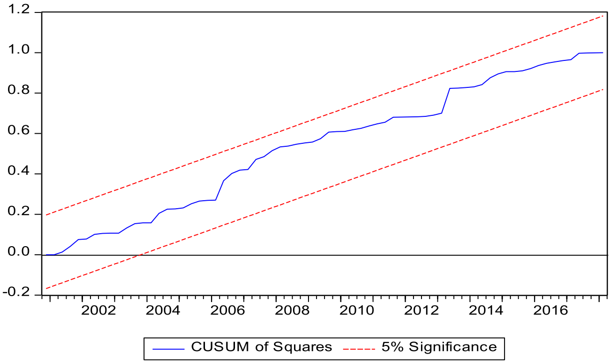

Fig. 3 Plot of cumulative sum square (CUSUM^2) Source: Authors' computation

Table 6 Output of the long-run VAR Granger Causality/Block Exogeneity Wald tests Source: Authors' computation with EViews

	Source of causation (independent variables)					
Dependent variable	GHGMPC1	FINDEV	GDPPC	EXDIVIN	PATENT	TRE
GHGMPC1	–	5.664** (0.0589)	2.336 (0.3109)	4.428 (0.1093)	3.028 (0.2199)	10.389** (0.0055)
FINDEV	12.982** (0.0111)	–	1.556 (0.4593)	12.229** (0.0022)	34.380* (0.0000)	16.476* (0.0003)
GDPPC	9.000** (0.0111)	3.094 (0.2128)	–	6.136* (0.0465)	2.523 (0.2831)	3.086 (0.2137)
EXDIVIN	1.181 (0.5540)	1.304 (0.5209)	0.278 (0.8701)	–	1.000 (1.148)	1.148 (0.5631)
PATENT	0.292 (0.8638)	0.165 (0.9205)	0.279 (0.8695)	0.474 (0.7888)	–	0.388 (0.8234)
TRE	5.750*** (0.0564)	4.311 (0.1158)	10.598* (0.0050)	8.290** (0.0158)	5.583*** (0.0613)	–

*, **, and *** denote 1%, 5%, and 10% significance level. Parenthesis numbers represent the *P* value

Table 7 Output of the short-run VAR Granger Causality/Block Exogeneity Wald tests Source: Authors' computation

	Source of causation (independent variables)					
Dependent variable	D(GHGMPC1)	D(FINDEV)	D(GDPPC)	D(EXDIVIN)	D(PATENT)	(DTRE)
D(GHGMPC1)	–	0.501 (0.4790)	0.452 (0.5011)	0.788 (0.3746)	0.016 (0.8977)	10.389* (0.0055)
D(FINDEV)	46.868* (0.0000)	–	0.335 (0.5626)	40.755* (0.0000)	5.383** (0.0203)	20.394* (0.0000)
D(GDPPC)	0.419 (0.5171)	0.185 (0.6671)	–	0.119 (0.7294)	0.175 (0.6752)	1.22 (0.9991)
D(EXDIVIN)	0.019 (0.8890)	0.237 (0.6258)	0.195 (0.6581)	–	0.063 (0.8007)	0.204 (0.6512)
D(PATENT)	0.006 (0.9350)	1.438 (0.2303)	3.959** (0.0466)	0.596 (0.4398)	–	0.608 (0.4355)
D(TRE)	0.673 (0.4118)	1.399 (0.2369)	17.418* (0.0000)	0.865 (0.3523)	0.038 (0.8447)	–

* and ** denote 1% and 5%. The numbers are the Chi-square statistics. The number in parentheses s represents the *P* value

and South Africa, respectively. Granger causality run from economic expansion to GHG emissions in the long period unidirectionally. There is no feedback mechanism between the outward diversification and GHG releases in the long period. Additionally, in the long run, there is a feedback hypothesis between finance and total renewables, and export diversification; economic growth and export diversification, total renewables and income expansion, and total renewables and technological innovation. These outputs are in support of Zoaka et al. (2022) and Shahbaz and Lean (2012), Zhang et al. (2022), Udemba et al. (2022). Shahbaz and Lean (2012) found a feedback mechanism between energy use and financial development in Tunisia. Zoaka et al. (2022) found that there is a feedback mechanism between financial development, economic expansion, finance, and renewable energy for BRICS countries. This output is insightful on the importance of financialization and technological innovation in determining the environmental sustainability of China.

In the short run, the output of VAR Granger Causality/Block Exogeneity Wald tests in Table 7 reveals that financial development Granger-cause GHG emissions unidirectionally in the short run. There is no feedback mechanism between export diversification, technological innovation, renewable energy, economic expansion, and GHG release in the short period. Additionally, there is a feedback link between export diversification, technological innovation, clean energy, and financial development; technological innovation and income expansion; renewables and income expansion. These outputs are insightful on the importance of financialization and technological innovation in determining the environmental sustainability of China in both the long and short run.

5 Conclusion and policy recommendations

Along with being the second largest economy in the world, China holds the top position for emitting carbon emissions due to excessive use of non-renewable energy sources for huge domestic economic activities including industrial production to meet domestic demand and enhance exports. China alone is producing more than a quarter of all global emissions. Improvement of environmental quality through the reduction of emission levels is therefore a main policy agenda of the Chinese government. This is required for the betterment of China and the world community. Realizing the importance of this vital issue, this study has, thus, attempted to investigate the roles of certain drivers in producing emission levels in China. We have particularly looked at the consequences of financial development, renewable energy, technological innovation, and export diversification to achieve long-term environmental quality in China. Using quarterly data from 1995Q1-2018Q4, we have applied the popular ARDL model and Granger causality test for empirical investigation. Our findings reveal that the EKC hypothesis for financial development is valid, and renewable energy and technological innovation have beneficial effects on the environmental quality while economic growth and export diversification have detrimental effects on the environment of China.

Based on our findings, the general policy recommendation is that the Chinese government should enhance the production and use of renewable energy and pursue technological innovation for green growth through financial development. Some specific policy measures would be as follows:

(i) *Increasing the production and use of clean energy:* Clean energy usage mitigates emissions. Therefore, the proportion of clean energy must be raised in the energy mix. To accelerate the clean energy production level, the Chinese government should increase investment, through financial development policy, in the renewable energy sector such as solar, wind power, and biomass. However, hydroelectric power has the highest potential in China (Adu et al. 2022). Investment through public and private partnerships will be a useful strategy, and the government should provide different incentives for producing and using renewable energy. Current subsidy procedures should be standardized, and supervision of fund utilization should be strengthened. An effective energy policy, prioritizing the production and use of renewable energy, will help to attain environmental quality.

(ii) *Increasing investment in technological innovation*: Adequate measures should be taken for maximizing the environmental impact of ecological innovation to improve environmental quality. Expenditures must be increased via financial development mechanisms and research and development in green technologies. Policies related to green strategies, ecological innovation, and environment-friendly technology can help environmental degradation and enhance the opportunity for sustainable development. Efforts should be made to electrify energy demand as much as possible with the aim of fully decarbonizing the electricity supply.

(iii) *Environment-inclusive financial development:* development of the financial sector expedites the economic growth of a country. Achievement of sustainable development and green financial development is required to mitigate emissions of CO_2 emissions. Thus, financial developmental actions and policies that are environmentally friendly are recommended for China to reduce pollution levels. Bank credit is to be made in low-carbon industries and energy-saving enterprises. Green financial cooperation should be established and enhanced.

(iv) *Export diversification plans and Improvement of export quality*: As export diversification is found detrimental to the environment, China should take proper plans for new product promotion, diversification of its export, and their trading partners to reduce emission levels. Hence, an improvement in the standard of export by making emphasizing more eco-friendly, cleaner, and efficient manufacturing methods for manufacturing items will contribute to emission reduction. Therefore, an extensive and broad-spectrum policy effort to upgrade the export standard is required to raise the quality of the environmental quality without compromising the desired growth economically.

(v) *Sustainable economic growth:* Economic growth has to be sustainable that takes into account environmental protection. Therefore, formulation and enactment of inclusive economic growth policies that are sustainable and inclusive without revital for mitigating emissions of CO_2. To ensure sustainable development in the long run, there is no alternative but to accommodate green energy usage, green industrialization, green urbanization, green technology, and green economy, clean tech, clean urban development. Similar to other numerous studies, the present study has some limitations also. We had to limit our study period relatively short, 1995Q1-2018Q4, due to the lack of required data. A longer data period would probably provide even better results. Furthermore, some policy variables such as the government's action plans and government effectiveness may also play a role in CO2 emissions reduction. Also, an examination of sector-wise CO2 emissions (e.g., industrial sector, agricultural sector) can provide a better insight as well. Future studies can be made addressing these issues.

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Data availability Authors declare the data will be made available on request.

Declarations

Conflict of interest Authors declare that there is no conflict of interest among the team in the course of this research.

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