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Dynamic Role of Green Energy Efficiency and Climate Technologies in Realizing Environmental Sustainability: Fresh Insights From China

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Amid rising industrialization and economic progress, China has shown exponential growth in energy and fossil fuel consumption; therefore, it faces great global concern and widespread criticism for energy and fuel conservation to reduce fuel-related emissions. In addition, the recent spread of COVID-19 instigates the impact of environmental pollution, exaggerates the virus intensity, and lowers people's immunity due to poor air quality. Therefore, this study explored the role of green energy efficiency and climate technologies in achieving carbon neutrality in China using an advanced quantile autoregressive distributed lag (QARDL) framework. The results indicated that green energy efficiency and climate technologies significantly reduce environmental pollution across all quantiles in the long run. In contrast, urbanization enhances environmental degradation at lower and higher emissions quantiles, while trade only promotes environmental pollution at lower quantiles. These findings suggested using alternative energy sources and carbon-reducing technologies to ensure a sustainable environment.

Keywords: green energy efficiency, renewable energy, climate technologies, environmental pollution, COVID-19

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INTRODUCTION

Energy is vital for economic stability, and its demand has continuously grown worldwide (Asiedu et al., 2021). However, its ecological implication has started from its exploration and exploitation and finally from its consumption (Osiyevskyy et al., 2020). Moreover, the rapid growth of industrialization caused the excessive use of energy and increased the divestment of fossil fuels (Pata, 2018; Sun et al., 2022a). The world's major industrial countries are dependent quite heavily on inevitably depleted fossil fuels. Getting control of the climate changes invariably, governments are now seeking ways to reduce the consumption of carbon-laden fuels (Ahmad et al., 2022; Atchike et al., 2022). For instance, these issues can be valuably responded to by reducing energy consumption, developing green energy sources, and improving energy efficiency (Razzaq et al., 2021a; Irfan et al., 2021; Sun et al., 2022b; Elavarasan et al., 2022).

Since 1978 after the reforms and opening up toward the sustainable path, China's economic growth has mainly depended on the high consumption of nonrenewable energy resources (Lu et al., 2019). The ongoing accelerated pace in China's total energy consumption accounts for almost 23.6% of the complete energy depletion of the world in 2018 (K. Dong F. et al., 2018; Lei et al., 2022) and

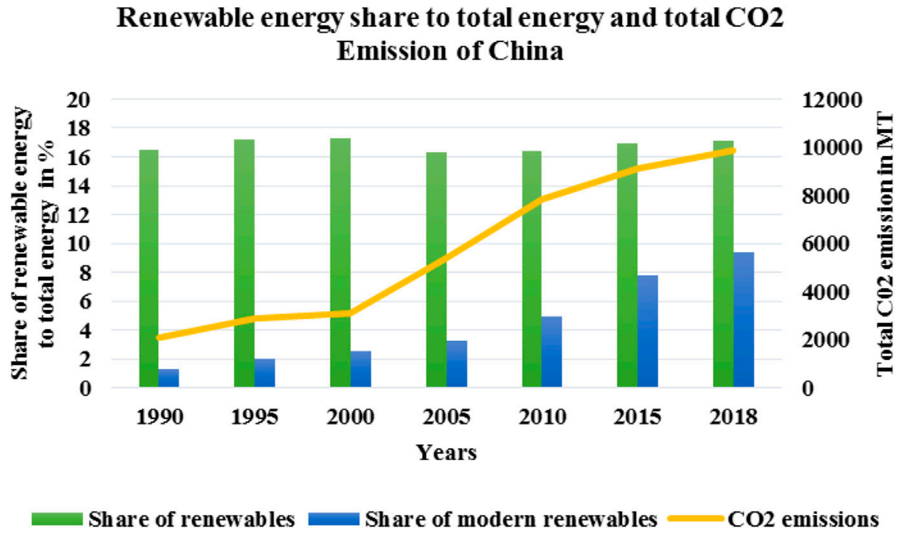

FIGURE 1 | Renewable energy share to total energy and total CO_2 emission of China. Source: IEA Sustainable Development Goal 7 https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2021.

contributed more than 34% of the net increase of global energy utilization. Moreover, the energy consumption growth rate reached 4.3% in China, which is relatively higher than the global average growth in energy consumption in 2018 (Liu et al., 2021a). Global energy growth is outpacing decarburization despite the positive progress of many countries whose economies have grown over the last decade, and their emissions have declined due to the replacement of energy-dense nonrenewable energy with green energy sources and the improvement in energy efficiency (reliance on eco-innovation) (Brown, 2021; Song et al., 2021; Fang et al., 2022; Sun and Razzaq, 2022). China is the largest energy consumer, and greenhouse gas emitter faces great global concern and widespread criticism for energy conservation and GHG emanation decline (Song et al., 2021; Yu et al., 2019; Sun et al., 2022b).

Green energy efficiency is necessary to meet the rapidly growing energy demand and the targets against climate change with sustainable development (Wu et al., 2021). In this regard, as per the Paris Agreement, China has set a target of 60–65% reduction in its emission intensity (the emission intensity is measured as the amount of GHGs released against the economic activity of per dollar) over 2005 levels in 2030 (P. Li and Ouyang, 2020; Miao et al., 2021). According to **Figure 1**, the share of renewable energy to the total energy is 17.11%, whereas the total CO_2 emission reached 9,876.5 MT in 2018. Moreover, according to the China Electric Power Yearbook for 2020, the current thermal and hydropower energy generation data state that hydropower contributes up to 68.9%; in contrast, thermal power is accounted for 17.8% of total power generation in China.

Energy efficiency refers to less consumption of energy resources while ensuring the same production level. It is the elimination of energy waste in production or any other economic activity (Liu et al., 2021b). According to the International Energy Agency (IEA), "Energy efficiency is key to ensuring a safe, reliable, affordable and sustainable energy system for the future. It is the only energy resource that every country possesses in abundance and is the quickest and least costly way of addressing energy security, environmental and economic challenges".

Improvement in green energy efficiency (GEE) ensures improved energy supply security, which is decisive for sustainable development (Murshed et al., 2020; Miao et al., 2022). Moreover, ramping up green energy efficiency by deploying green innovations, smart grids, and new green transport technologies contribute to curtailing greenhouse gas emissions, reducing the imported energy demand, and lowering the energy cost of households and the economy. Moreover, green energy efficiency has vast opportunities for each economic sector, such as manufacturing, transportation, real estate, and energy production, in terms of pollution control. China has significantly improved its industrial energy efficiency in the last couple of years by investing in technology innovations of RE resources (Irfan et al., 2020; Ling et al., 2021). However, there is still a significant demand and supply gap for which the improvement of GEE is the crucial step to reducing carbon intensity and energy protection.

Similarly, various studies have pronounced technology innovation as crucial for economic growth. However, these innovations boost not only financial actions but also spur environmental degradation (Chien et al., 2021a), whereas eco-innovation (as green innovation proxy) is a pivotal means of economic sustainability and an effective means to reduce the emanation of greenhouse gases (Ali et al., 2021). Eco-innovations (ECO) is "the adaptation of new concepts, ideas, and technologies for the procedural development of economic restructuring and optimization". The enhancement of ECO enables countries to transform the traditional economic structure into a more energy-efficient production structure (Chien et al., 2021b; Ding et al., 2021; Hu et al., 2022).

Most of the existing literature has explored the dynamic relationship between renewable energy and carbon emissions, such as Chen et al. (2019), Chien et al. (2021c), Lin and Zhu (2019), and Wang B. et al. (2018), energy efficiency (Yu et al., 2019; Wang et al., 2021; Chien et al., 2022), and eco-innovation and carbon emission (Afshan and Yaqoob, 2022; Chien et al., 2021a; Hsu et al., 2021; Jin et al., 2021) for China. However, no such study explains the role of GEE and ECO on CO_2 in China. As discussed earlier, China is a significant greenhouse gas emitter and nonrenewable and the largest energy consumer; thus, for China, the role of GEE and ECO is crucial to pursuing the environmental sustainability objective. Therefore, to respond to the gap, the current study explores the role of green energy efficiency (GEE) and eco-innovation (ECO) on environmental pollution (CO_2) in China along with two control variables such as urbanization (URB) and trade (TRD). Moreover, the study's outcomes will provide insights for establishing better policies.

Moreover, to examine the relationship between GEE, ECO, URB, and TR and CO_2 more precisely, the study employs the QARDL (quantile autoregressive distributed lag) method. This method of estimations is advantageous over the other traditional regression analysis methods in many ways; for instance, this method considers the magnitude, such as quantiles to get parameter estimates and elaborates the association among the study variables in the long run and short run. These estimates provide more reliable, accurate, and detailed relationships. Moreover, the QARDL method incorporates the potential asymmetric and nonlinear relationship between the GEE, ECO, URB, and TR and CO_2 (Cho et al., 2015; Hsu et al., 2021; Ji et al., 2021; Jin et al., 2021; Sharif et al., 2020; Song et al., 2021). Thus, based on these motivations, the study incorporated the QARDL as the most effective method for the analysis.

The study's outcomes illustrate that the GEE and ECO significantly reduce carbon emissions at all pollution levels in the long run. At the same time, URB enhances carbon emission at lower and significant pollution levels in the long run, while TRD only harms the quality of the environment at the low level of pollution in China in the long term. However, for the short-term impact, it has been observed that GEE significantly decreases CO_2 at a low pollution level while ECO drops CO_2 significantly at a high pollution level. At the same time, URB promotes CO_2 at all levels of pollution, while TRD only promotes CO_2 at the low level of pollution.

The remaining part of the study is structured as follows: section 4 discusses the relevant studies that already explored relationships among the study variables. Section 3 defines the variables data source and the QARDL model from a theoretical perspective. Moreover, **section 4** interprets the outcomes of all incorporated tests. Section 5 summarized the analysis in the form of a conclusion and suggested some policy recommendations based on that conclusion.

LITERATURE REVIEW

Recent studies have a growing concern to explore the ways to reduce environmental pollution and obtain economic and environmental sustainability. As discussed earlier in the introduction section, various recent studies have accounted for different driving factors to control environmental degradation in China, for instance, RE resource consumption (Khattak et al., 2020; Godil et al., 2021), technological innovations (Shahbaz et al., 2020), green innovation (Hu et al., 2022), industrialization (Dong K. et al., 2018; Wang and Su, 2019), globalization (Ling et al., 2021), economic growth (Liu et al., 2019), trade openness (Liu et al., 2021a), environmental regulations (Li et al., 2022), environmental taxes (Hsu et al., 2021), tourism (Razzaq et al., 2021a), FDI inflows (Shahbaz et al., 2020), and financial development (Godil et al., 2020). It has been observed that the existing literature does not provide any single study which has addressed the role of green energy efficiency on environmental degradation in China. Therefore, the current study incorporates the variable of green energy efficiency first time to investigate its impact on environmental pollution in China. Moreover, this section compiles the existing literature on the study variables.

Green Energy Efficiency and Environmental Pollution

Renewable energy implies a decrease in nonrenewable energy consumption and mitigates the detrimental effect of environmental pollution (Razmjoo et al., 2021). Similarly, energy efficiency is also decisive in controlling carbon emissions (Qin et al., 2020; Irfan et al., 2022); therefore, green energy efficiency is considered the foremost tool to mitigate the adverse effects of greenhouse gases (GHGs). There is no such study that accounts for the green or renewable energy efficiency specifically to analyze. However, few studies incorporate renewable energy and energy efficiency separately to examine their diminishing role in carbon emission (Bhadbhade et al., 2019; Chien et al., 2022; Dong F. et al., 2018; Guo and Pachauri, 2017; Huang et al., 2018; Shao et al., 2019; Wang et al., 2021; Zhang et al., 2017).

Gökgöz and Güvercin (2018) have evaluated the role of the GEE on the energy security of EU countries from 2004 to 2014. The study explored that renewable energy efficiency decreases with the increase in energy production; therefore, the emission level of GHGs is enhanced. Murshed (2020) has studied the indirect impact of ICT trade on CO_2 emission through energy efficiency in the South Asian economies. The outcomes of the panel estimation of CUP-FM suggested that the ICT trade enhances renewable energy consumption, leading to improved energy efficiency and environmental quality.

Furthermore, Akram et al. (2021) have also examined the impact of RE and energy efficiency on CO_2 for 66 underdeveloped countries. The findings of the quantile regression method are based on the panel data from 1990 to 2014 and endorse the negative impact of energy efficiency (EE) on CO_2 at high quantiles. In addition, Liu et al. (2021b) have investigated provisional policies' role in China's energy efficiency. The findings stated that the EE is the only way through which China can achieve its predefined goal of 2030 to reduce its fossil fuel consumption; therefore, by adopting low carbon technologies, China can rely more on renewable energy

TABLE 1 | Variable description.

Variable and symbol	Variable description	Variable data source
Dependent variable		
Environmental pollution—CO_2	Per capita CO_2 emission measured in metric tons per capita	World Bank (2020)
Independent variables		
Green energy efficiency—GEE	Measured as the ratio between renewable energy and GDP	British Petroleum
Eco-innovation—ECO	Measured as the number of registered green patents in the whole year	OECD
Urbanization—URB	Measured as the number of residents in the urban area or urban population	OECD
Trade—TRD	Measured as trade openness (Import + Export/GDP)	OECD

resources and improve its energy efficiency (Khan et al., 2021; Khan et al., 2022).

Another study by Li and Ouyang (2020) has explored the factors in the heavy industrial sector of china that can mitigate carbon emissions without compromising economic growth. The result of the study exhibited that clean energy consumption and the technological progress of EE can reduce the carbon intensity in China. Moreover, the studies by Bhadbhade et al. (2019), Chien et al. (2022), and Huang et al. (2018) have also found a negative association between energy efficiency and CO_2 (Irfan et al., 2019).

Nexus Between Eco-innovation and Environmental Pollution

The association between ECO and CO_2 has been analyzed by a vast number of studies (Khan et al., 2020; Chien et al., 2021b; Ding et al., 2021; Ji et al., 2021; Jin et al., 2021; Tao et al., 2021). ECO motivates the economies to adopt new technologies to reduce environmental pollution. It reduces traditional energy resource consumption by providing alternate solutions and controlling CO_2 (Ji et al., 2021; Hu et al., 2022). Ali et al. (2021) have analyzed the role of ECO to mitigate CO_2 in the top 10 GHG emitters of the world and found that the ECO negatively influences carbon emanation and enhances economic activities by promoting renewable energy resource consumption. Similarly, the outcomes of the study presented by Shahbaz et al. (2020) support the findings of previous studies and consider the ECO as the primary tool to control CO_2 in highly industrial economies.

Moreover, the finding of (Ji et al., 2021) study has redefined the impact of ECO on environmental quality. They explored that the highly fiscal decentralized economies experienced a significant decline in CO_2 in the long term due to ECO. Ding et al. (2021) have investigated the influence of ECO on CO_2 in G-7 countries from 1990 to 2018. The outcomes of the CS-ARDL estimator also endorse the mitigating impact of ECO on CO_2.

MATERIALS AND METHODS

Data Description

The current study attempted to explore the impact of GEE and ECO to control CO_2 in China; therefore, the study incorporates the data from 1995 to 2019 on carbon emission (CO_2) as dependent variables, green energy efficiency (GEE) and eco-innovation (ECO) as focus variables while the urbanization (URB) and trade (TRD) are taken as control variables. **Table 1** illustrates the details of the explained variables. This has been converted from annual to quarters following the match sum approach (Razzaq et al., 2021b). **Table 2** presents the detail descriptive statistics of model variables.

TABLE 2 | Results of descriptive statistics.

Variable	GEE	ECO	URB	TRD	CO_2
Mean	0.498	4.088	10.958	1.404	3.830
Minimum	0.428	3.265	3.000	1.147	2.210
Maximum	0.560	6.037	14.000	2.935	4.600
Standard deviation	0.045	0.851	3.076	0.189	0.250
Skewness	0.176	1.222	0.695	0.373	0.764
Kurtosis	0.603	0.063	0.175	0.041	0.883
Jarque–Bera	18.076	15.976	12.613	15.476	24.111
Probability	0.000	0.000	0.000	0.000	0.000

Source: author estimation

Theoretical Background and Methodology

The study intended to investigate the dynamic long-run correlation between green energy efficiency (GEE), eco-innovation (ECO), urbanization (URB), trade (TRD), and environmental pollution (CO_2) for China by employing the QARDL model introduced by Cho et al. (2015) which helps to test the long-run equilibrium effect of all variables on carbon emission across the different grids of quantiles. The relationship between the socioeconomic variables is not necessarily linear, as assumed by the general regression method of ordinary least squares (OLS) (Liu et al., 2021a; Razzaq et al., 2021a). Moreover, another econometric method known as ARDL (autoregressive distribution lag) considers the different order cointegration and determines only the cointegration among variables. Therefore, to alleviate the analysis's methodological deficiencies, this study incorporates the QARDL method.

QARDL method determines the nonlinear or asymmetric long-run and the short-run association between the variables over the different conditional distributions of the variables (Song et al., 2021). Moreover, for the robustness analysis and the time-varying integration, the study applied the Wald test, which allowed examining the dependency of parameters and steadiness of the integrated coefficient in each quartile (Godil et al., 2021; Song et al., 2021; Razzaq et al., 2022b). The ARDL model for this study is given as follows:

$$CO_{2t} = \alpha + \alpha_{GEE}\, GEE_t \; + \; \alpha_{ECO}\, ECO_t \; + \; \alpha_{URB}\, URB + \alpha_{TRD}\, TRD_t + \; \mu_t. \tag{1}$$

Equation 1 represents CO_2 as environmental pollution, GEE as the green energy efficiency, URB as the urban population or urbanization, and TRD as trade openness of China, whereas t represents the time dimension and the coefficients of variables illustrated as $\alpha_{GEE} = \frac{CO_{2t}}{GEE_t}$, $\alpha_{ECO} = \frac{CO_{2t}}{ECO_t}$, $\alpha_{URB} = \frac{CO_{2t}}{URB_t}$, $and\ \alpha_{TRD} = \frac{CO_{2t}}{TRD_t}$, while μ_t is defined as an error term in the model. Renewable energy implies a decrease in nonrenewable energy consumption and mitigates the detrimental effect of CO2 (Razmjoo et al., 2021). Similarly; energy efficiency is also decisive in controlling carbon emission (Qin et al., 2020); therefore, the GEE is expected to have a negative coefficient $\alpha_{GEE} = \frac{CO_{2t}}{GEE_t} < 0$ to describe the relationship with environmental pollution.

According to Su et al. (2021) and Sharif et al. (2020), technological innovations accelerate fossil fuel consumption, improve economic growth, and enhance environmental degradation. However, eco-innovation reduces the traditional energy resource consumption by providing alternate solutions and controlling CO_2 (Ji et al., 2021; Hu et al., 2022); therefore, the ECO is expected to reduce CO_2, such as $\alpha_{ECO} = \frac{CO_{2t}}{ECO_t} < 0$. Similarly, trade openness enhances production activities, leading to more energy consumption and becoming the reason for more carbon emissions (Lv and Xu, 2019). However, being an emerging country in China, trade attracts FDI inflows, enhancing investment opportunities in energy efficiency projects and reducing carbon emissions (Q. Wang and Zhang, 2021). Therefore, the TRD is expected to have a positive $\alpha_{TRD} = \frac{CO_{2t}}{TRD} > 0$ or a negative $\alpha_{TRD} = \frac{CO_{2t}}{TRD_t} < 0$ coefficient link with CO_2. On the contrary, China has currently transformed into a high-quality urbanization mode (Qi et al., 2020) where the services and free-market boost the economic growth and lead to high carbon emissions. Hence, the expected outcome is the positive $\alpha_{URB} = \frac{CO_{2t}}{URB_t} > 0$ coefficient of urbanization, with regards to carbon emission or environmental pollution (Afridi et al., 2019).

RESULTS AND DISCUSSION

Table 1 illustrates the outcomes of the descriptive analysis of environmental pollution (CO2), green energy efficiency (GEE), eco-innovation (ECO), urbanization (URB), and trade (TRD). It has been observed that GEE has the lowest mean value of 0.498 between the range of 0.428–0.560. In comparison, URB has the highest mean value of 10.958, which lies between 3.00 and 14.00. Similarly, the highest standard deviation value is also demonstrated by URB, which is 3.076, while the least standard deviation of 0.045 is observed for GEE. Moreover, the Jarque–Bera statistic evaluates the normality among the variables. The results illustrated that all the variables meet the significance level of 1% and endorse that the data distribution is not normal. Therefore, this study is allowed to apply the QARDL method to obtain the regression estimates of the selected data (Sharif et al., 2020; Razzaq et al., 2021b; Chien et al., 2021c; Godil et al., 2021; Song et al., 2021).

TABLE 3 | Results of the unit root test.

Variable	GEE	ECO	URB	TRD	CO_2
ADF (level)	0.375	–1.275	–2.094**	–0.995	–1.739*
ADF (Δ)	–3.572***	–4.048***	–3.668***	–4.583***	–6.583***
ZA (level)	–1.048	–2.586	–0.587	–2.409	1.436
Year	2012 Q1	1999 Q4	2006 Q1	2015 Q1	2010 Q2
ZA (Δ)	–6.707***	–5.996***	–5.281**	–7.021***	–11.584***
Year	2016 Q4	2016 Q4	2008 Q3	2015 Q4	1997 Q1
Source: author estimation					

Notes: For stationarity, the values are specified in the matrix of the ADF and ZA.
****, **, and * indicate a level of significance at 1, 5, and 10%, respectively.*

In the time-series data, it is crucial to ensure the integration order of the series before applying the QARDL model for estimations (Razzaq et al., 2021c; Song et al., 2021). Therefore, this study conducted the ZA (Zivot–Andrew) and ADF (Augmented Dickey–Fuller test) unit root tests to determine whether the time series data are stationary. However, the ZA test has more importance because it considers the structural break. **Table 3** presents the estimates of the ADF and ZA test, which affirm the non-stationarity of variables at the level. However, ZA and ADF test results reject the null hypothesis and endorse all variables' stationarity at the first difference at 1 and 5% significance levels. Based on these results, it has been assumed that the QARDL is the most appropriate method for estimations that account for the structural break, nonlinearity, and dynamic trend in the data (Sharif et al., 2020; Godil et al., 2021).

Table 4 illustrates the estimates of the QARDL methods. The test outcomes revealed the interaction between the GEE, ECO, URB, TRD, and CO_2. Moreover, the parameter of ECM or the value of ρ^*, also known as the parameter of the speed of adjustment, is negative and significant at the low, middle quantile (0.05–0.50), and high quantile (0.80–0.95) and proves the presence of the reversal toward the equilibrium in the long run between the selected variables. The nexus between GEE-CO2 is supposed to be negative in China because the green energy efficiency reduces carbon emission. In the last couple of years, China has heavily invested and subsidized various green energy projects such as FIT schemes and the subsidies for Solar PV installation, which has enhanced the green energy efficiency to work as a catalyst to reduce CO2. In the long run, the coefficient value of GEE is negative and significant across all quantiles, which proves that energy efficiency is used as the appropriate tool to curb environmental pollution. The finding is supported by the recent studies (Chien et al., 2022; Gökgöz and Güvercin, 2018; Li et al., 2022; Xu et al., 2021; Zhou et al., 2018).

Similarly, the results from **Table 4** revealed that the ECO has a significantly negative association with CO_2 at all quantiles in the long run which has proven that ECO is the adaptation of advanced technology to prevent the waste of energy resources, promote a green economy, and ultimately control carbon emission. Eco-innovation is considered the main component of policy formulation related to environmental sustainability. It reduces the pollution of the

TABLE 4 | Long-short run estimates of quantile ARDL estimations.

Quantile (τ)	Constant	ECM	Long-run estimates				Short-run estimates						
	$\alpha_*(\tau)$	$\rho_*(\tau)$	$\alpha_{GEE}(\tau)$	$\alpha_{ECO}(\tau)$	$\alpha_{URB}(\tau)$	$\alpha_{TRD}(\tau)$	ϕ_1 (τ)	ω_o^{GEE} (τ)	ω_1^{GEE} (τ)	γ_o^{ECO} (τ)	γ_1^{ECO} (τ)	θ_o^{URB} (τ)	δ_o^{TRD} (τ)
0.05	0.109	−0.084***	−0.510***	−0.103***	0.355*	0.669**	0.449***	−0.039***	−0.036	−0.111	−0.044	0.007*	0.249***
	(0.073)	(0.017)	(0.021)	(0.019)	(0.203)	(0.281)	(0.081)	(0.010)	(0.298)	(0.149)	(0.794)	(0.004)	(0.075)
0.10	0.277***	−0.220***	−0.461***	−0.125***	0.355	0.610**	0.404***	−0.039***	−0.025	−0.178	−0.052	0.007***	0.124***
	(0.055)	(0.044)	(0.038)	(0.037)	(0.222)	(0.270)	(0.050)	(0.010)	(0.299)	(0.288)	(0.496)	(0.002)	(0.040)
0.20	0.087**	−0.258***	−0.383***	−0.129***	0.532**	0.771**	0.486***	−0.039***	−0.002	−0.207	−0.022	0.007***	0.124***
	(0.037)	(0.029)	(0.041)	(0.025)	(0.250)	(0.270)	(0.045)	(0.012)	(0.259)	(0.139)	(0.430)	(0.002)	(0.041)
0.30	0.095**	−0.294***	−0.352***	−0.144***	0.177	0.357**	0.505***	−0.039**	−0.002	−0.178	−0.044	0.007**	0.198***
	(0.036)	(0.028)	(0.051)	(0.025)	(0.261)	(0.160)	(0.060)	(0.020)	(0.199)	(0.139)	(0.397)	(0.003)	(0.042)
0.40	0.139***	−0.112***	−0.302***	−0.141***	0.355	0.119	0.515***	−0.313	−0.003	−0.170	−0.022	0.015***	0.171***
	(0.039)	(0.031)	(0.045)	(0.023)	(0.301)	(0.171)	(0.041)	(0.260)	(0.298)	(0.139)	(0.340)	(0.003)	(0.043)
0.50	0.152***	−0.122***	−0.250***	−0.217***	0.355	0.119	0.522***	−0.106	−0.006	−0.155	−0.022	0.044***	0.373
	(0.041)	(0.033)	(0.031)	(0.021)	(0.312)	(0.201)	(0.052)	(0.301)	(0.199)	(0.189)	(0.304)	(0.003)	(0.282)
0.60	0.033	−0.033	−0.166***	−0.198***	0.355**	0.139	0.445***	−0.159	−0.009	−0.052	−0.015	0.067***	0.124
	(0.039)	(0.031)	(0.023)	(0.025)	(0.151)	(0.192)	(0.059)	(0.321)	(0.130)	(0.199)	(0.250)	(0.004)	(0.320)
0.70	−0.022	-0.016	−0.129***	−0.202***	2.128***	0.219	0.423***	−0.200	−0.002	−0.007	−0.007	0.007*	0.124
	(0.039)	(0.031)	(0.011)	(0.035)	(0.172)	(0.190)	(0.059)	(0.360)	(0.110)	(0.158)	(0.204)	(0.004)	(0.353)
0.80	−0.044	-0.413***	−0.113***	−0.194***	1.125***	0.278	0.404***	−0.225	−0.005	−0.159*	−0.022	0.015***	0.124
	(0.042)	(0.033)	(0.015)	(0.046)	(0.195)	(0.190)	(0.061)	(0.415)	(0.099)	(0.088)	(0.197)	(0.004)	(0.393)
0.90	−0.076	−0.465***	−0.160***	−0.160***	0.801***	0.297	0.392***	−0.290	−0.006	−0.196**	−0.163	0.037***	0.498
	(0.047)	(0.038)	(0.018)	(0.030)	(0.208)	(0.172)	(0.053)	(0.420)	(0.091)	(0.081)	(0.160)	(0.005)	(0.430)
0.95	0.041	−0.522***	-0.240***	−0.175***	0.700***	0.233	0.402***	−0.303	−0.003	−0.226***	−0.252	0.022***	0.373
	(0.046)	(0.037)	(0.023)	(0.032)	(0.212)	(0.188)	(0.059)	(0.443)	(0.089)	(0.041)	(0.156)	(0.005)	(0.470)

*Note: The table shows coefficient and standard error in brackets. Moreover, ***, **, and * indicate a level of significance at 1, 5, and 10%, respectively.*
Source: author estimation.

environment with the mutual influence of the other economic variables, for instance, energy efficiency, renewable energy resources, and the development of infrastructure and production mechanisms to reduce the dependency on traditional energy recourse. The result is aligned with previous study results (Hu et al., 2022; Ji et al., 2021; Khattak et al., 2020; Shao et al., 2021).

Moreover, in the long run, the coefficient of URB shows a positively significant impact on CO_2 at the lowest quartile (0.05) at a 10% level of significance. In contrast, at a low quantile (0.2), the effect is positive but significant at 5% significance, while at the medium to high quartile (0.60–0.95), the influence is positive and highly significant, indicating that urbanization puts environmental pressure on the economy at a high pollution level. The increase in urbanization drives industrial production accelerating energy demand and infrastructure development, increasing the consumption of nonrenewable energy resources, and enhancing carbon emissions. The findings are supported by recent studies (Afridi et al., 2019; Huang et al., 2021; Wang and Su, 2019; Wang S. et al., 2018; Yao et al., 2021).

Similarly, the outcome for the nexus between TRD and CO_2 revealed that TRD has a positive impact on environmental pollution across all quantiles. However, it is significant only at a lower quantile (0.05–0.30) at the 5% level of significance, which exhibits that the increase in trade activities accelerates the carbon emission at the low pollution level in China. Trade has an essential role in enhancing production activities and economic development, leading to more energy consumption and becoming the reason for more carbon emissions in the long run. This result is in line with the existing studies (Du et al., 2019; Lv and Xu, 2019; Wang and Zhang, 2021), whereas the findings are contrary to the results of Wang and Zhang (2021).

On the other hand, to evaluate the short-run dynamics of analysis (**Table 4**), the study's findings revealed that variation in the present CO_2 is significantly enhanced by their previous level in China at all quantiles at a 1% level of significance. The accumulated variation of past and present GEEs negatively and greatly influenced the current CO_2 level at the lowest to low quantiles (0.05–0.20) at the 1% significance level. In comparison, at the middle quantile (0.30), the impact remains significantly opposite at 5% significance, indicating that green energy efficiency combats the carbon emission at a low pollution level in China in the short run. Similarly, the combined variation of previous and current ECO significantly reduces the current level of CO_2. However, this negative impact remains significant only at high to the highest quantile of (0.80) at 10%, (0.90) at 5%, and (0.95) at 1% level of significance, which has exhibited that the ECO can only help reduce the carbon emission at a high pollution level in the short run.

Moreover, in the short run, the past and present changes in URB significantly promote the current changes in CO_2 across all quantiles. In contrast, the cumulative variations in the current and previous TRD enhance the current level of CO_2 at the lowest to middle quantiles (0.05–0.40), representing that the TRD only increases the carbon emission at a low level of environmental pollution. Hence, the overall outcomes of the

TABLE 5 | Results of the Wald Test for the constancy of parameters.

Variable	Wald statistics [*p*-value]
ρ	3.978*** [0.000]
α_{GEE}	5.381*** [0.000]
α_{ECO}	4.004*** [0.000]
α_{URB}	7.481* [0.000]
α_{TRD}	5.559** [0.000]
$\varphi 1$	6.039*** [0.000]
$\omega 0$	2.685** [0.048]
$\omega 1$	0.381 [0.931]
γ 0	7.904*** [0.000]
γ 1	0.478 [0.853]
$\theta 0$	3.094*** [0.001]
$\delta 0$	4.113*** [0.000]
Short-term cumulative effect	
ω^*	0.105 [0.999]
γ_*	1.094 [0.251]

Source: author estimation

QARDL model revealed that for China, the GEE and ECO have a negative influence, whereas URB and TRD have a positive influence on CO_2 in the long run and the short run at different pollution levels.

The Wald test results presented in **Table 5** confirm the long-run and short-run asymmetric associations of the GEE, ECO, URB, and TRD with CO_2. The outcomes to check the consistency or stability of the parameter revealed that the null hypothesis of the linearity of the speed of adjustment parameter has been rejected. Similarly, the hypothesis of long-run parameters consistency has also been rejected by the coefficients of α_{GEE}, α_{ECO}, α_{URB}, and α_{TRD}. These outcomes endorse that GEE, ECO, URB, and TRD have a high correlation with CO_2 in the long run. Moreover, in short-run dynamics, the collective effects of the past level of CO_2 on the current level of CO_2 are positive and significant, which also rejects the null hypothesis. The same results of the nonlinear and significant collective influences of GEE, ECO, URB, and TRD on CO_2 have been observed in the short run. Additionally, **Table 5** also demonstrated that the Wald test failed to reject the null hypothesis of parameter consistency for the cumulative effect of the GEE and ECO on CO_2 at lag 1.

CONCLUSION AND POLICY RECOMMENDATIONS

The current study investigated the relationship between GEE, ECO, URB, TRD, and CO_2 in China. The study employed the quarterly time-series data from 1995 to 2019 and applied the most appropriate and advanced quantile autoregressive distributed lag (QARDL) method to get detailed, reliable, and accurate estimates. The study's empirical finding reveals that green energy efficiency and eco-innovation significantly reduced environmental pollution in the long run. China has heavily invested in and subsidized various green energy projects such as FIT schemes and the subsidies for solar PV installation, which has enhanced the green energy efficiency to work as a catalyst to reduce environmental degradation. The negative association of the GEE with CO_2 proves that energy efficiency can be used as the appropriate tool to curb environmental pollution (Chien et al., 2022; Xu et al., 2021; Zhou et al., 2018).

Similarly, the negative correlation between ECO and CO_2 also endorses that the ECO is considered the main component of policy formulation related to environmental sustainability. It enhances the efficiency of renewable energy resources, prevents energy waste, and promotes a green economy by reducing carbon emissions (Khattak et al., 2020; Ji et al., 2021; Tao et al., 2021; Hu et al., 2022). At the same time, urbanization enhances environmental degradation at low and high quantiles. The increase in urbanization drives industrial production and accelerates energy demand and infrastructure development, leading to the increased consumption of nonrenewable energy resources and carbon emissions (Afridi et al., 2019; Huang et al., 2021). When trade or trade openness only promotes environmental pollution in low quantiles, an increase in trade activities accelerates and causes environmental degradation (Du et al., 2019; Wang and Zhang, 2021). However, the findings remain the same in the short run except for the green energy efficiency, which decreases CO_2 at a low quantile, and eco-innovation, which reduces CO_2 at a high quantile. Moreover, the study found bidirectional causality among all variables at all quantiles. Thus, it has been concluded that GEE and ECO are the most reliable ways to control CO_2 in China.

Based on the study's conclusion, the government of China should develop policies to promote green energy efficiency and eco-innovation for each sector of the economy. China has additional green energy efficiency potential, which has not yet been quantified due to the obstacles and barriers hampering the cost-effective technologies to improve green energy efficiency. By providing more incentives, the government of China can attract more private investors to boost the investment in green energy efficiency projects. Similarly, eco-innovation effectively promotes economic and environmental sustainability by breaking down the resources and environmental constraints. Therefore, implementing the environmental regulations enhances green energy efficiency, saves energy, and reduces carbon emission. Government and policymakers need to add green energy efficiency and eco-innovations in the planning of smart cities; they can construct green buildings and infrastructure to promote innovative heating, ventilation, and cooling system in urban areas to make more resilient cities. Similarly, optimal renewable energy resources and integrated energy services will make the production sector more intelligent and competitive.

Moreover, for the production sector, the authorities should also promote the investment in private venture capital in R&D related to improving green energy efficiency and eco-innovation by reducing the corporate taxes on energy-saving and energy management projects. Furthermore, the private venture capital will also support the startups to improve green energy efficiency sector-wise. Despite the investment, there is also a need to create awareness and strong skills by knowledge sharing to obtain the maximum benefit of green energy efficiency in terms of business case investment and green energy efficiency business measures. In addition, the inclusion of green energy efficiency standards in the municipal regulations will help the local government adopt the energy efficiency measures to consider environmental sustainability in the city's expansion plans and new building construction.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

ZL presented the research's idea and design, and CQ applied the model and drafted the manuscript.

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