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Retesting the Influences on CO2 Emissions in China: Evidence From Dynamic ARDL Approach

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This study aims to demonstrate the impact of economic growth and energy consumption on environmental degradation in China, the top country that produced the highest carbon dioxide ($CO_{2)}$ emissions, by considering that environmental degradation is one of the extreme challenges that the world and China have been facing. Parallel to this aim, this study uses dynamic ARDL (DYNARDL) simulations to investigate the long-run and short-run cointegration amongst the selected parameters from 1979 to 2019. The results of the long-run and short-run simulations illustrate that 1) economic growth increases environmental degradation; 2) growth in energy consumption worsens the environmental degradation situation; 3) urbanization improves the environmental situation in the long run, whereas growth in urban population increases CO_2 emissions in the short-run. The research argues that improved energy production and management should be included in economic policy planning and the government should invest more in renewable energy to prevent environmental degradation.

Keywords: DYNARDL model, environmental degradation, economic growth, energy consumption, urbanization

1 INTRODUCTION

One of the most important issues affecting the modern world is environmental degradation (Li et al., 2021; Liu et al., 2021). This is because it has negative consequences for human health, biodiversity, the ozone layer, quality of air, natural resources (e.g., water, soil, and forest), and the overall economy (Rehman et al., 2021b). High CO_2 emissions have been influencing both developed and developing countries throughout the world. CO_2 emissions are one of the main factors that cause environmental degradation (Adebayo et al., 2021; Satrovic et al., 2021). Despite international organizations' efforts to mitigate its negative impact on the environment and formulate measures to reduce CO_2 emissions, still global energy-related CO_2 emissions increased by 53.7% in the last 30 years and reached 31.5 gigatonnes in 2020, which is 5.8% less than in 2019 due to the COVID-19 pandemic and resulting in an economic crisis (IEA, 2021). Furthermore, just a few nations are responsible for the majority of this pollution (Magazzino et al., 2020a). For example, China accounts for over 30% of global emissions, while the United States (US) generates almost 14%, India produces more than 7% according to the 2020-years end figures (WorldBank, 2021).

Energy consumption, particularly from oil, gas, and coal sources, is the primary cause of CO_2 emissions (Koengkan and Fuinhas, 2021b; Chopra et al., 2022). Energy is the basis of a country's economy because it permits investments and technologies that lead to job creation and economic progress (Bildirici and Gokmenoglu, 2020; Fan et al., 2020). Energy and other natural resources are being used by countries to achieve and sustain economic growth (Mele and Magazzino, 2020; Fan and Zhang, 2021). It can be predicted that countries' overall energy consumption will increases as economies expand (Bashir et al., 2020; Talbi et al., 2020). As a result, it is critical to understand how to reduce CO_2 emissions while maintaining the current growth rate.

Environmental degradation is generally caused by several factors. Human-related factors like energy consumption and economic growth are among the leading causes of environmental degradation (Guo et al., 2022b). Energy consumption is a vital component of economic growth in most developing countries since it supports a wide range of economic activities (Nathaniel and Bekun, 2021). Although energy consumption, overall, stimulates economic growth (Koengkan and Fuinhas, 2020), the type of energy resource utilized determines the environmental quality (Shahzad et al., 2021).

The cointegration between economic growth and environmental quality was deeply examined under the conceptual framework of the Environmental Kuznets Curve (EKC) hypothesis (Kuznets, 1955; Grossman and Krueger, 1995), which states that a country may boost environmental degradation with economic growth, but that as economic growth increases, the level of environmental degradation decreases (Rothman, 1998). The EKC implies an inverted U-shaped nexus between economic growth and pollution (Kuznets, 1955). Some studies support the existence of EKC (Ali et al., 2020; Ulucak et al., 2020), whereas others do not confirm EKC (Rahman et al., 2020; Pata and Isik, 2021). This ambiguity in the literature comes from factors such as the selection of countries, period, and difference of parameters in the model, selection of quadratic or cubic EKC model, socioeconomic characteristics of the examined country, and selection of econometric methodologies. Even in some cases when the EKC is evaluated for the same country, different findings are obtained (Mehmood and Tariq, 2020).

CO_2 emissions have caught the interest of researchers, with evidence indicating that energy consumption (Nurgazina et al., 2021), population (Dong et al., 2018), human capital (Bano et al., 2018), urbanization (Wang et al., 2016), financial development (Khan et al., 2022), research and development (Danish et al., 2018), trade openness (Kwakwa et al., 2018), use of natural resources (Umar et al., 2020), and globalization (Pata, 2021) among other factors, are important determinants of CO_2 emissions.

Several studies (Liu et al., 2020; Nathaniel et al., 2020) discover that economic growth, use of the natural resource, urbanization, and globalization are responsible for the increase in CO_2 emissions. For instance, Liu et al. (2020) find that economic growth and globalization increase CO_2 emissions, but renewable energy reduces CO_2 emissions. Haseeb et al. (2018) investigate that urbanization and globalization negatively cause CO_2 emissions in BRICS economics. Moreover, the authors of the study examine that energy use and financial development play a positive role in enhancing CO_2 emissions. Saint Akadiri et al. (2019) define tourism, globalization, energy consumption are important determinants of CO_2 emissions significantly contributing to environmental degradation.

FDI inflows are the most important accelerator of economic growth because they facilitate the transfer of capital and technology to developing countries (Murshed, 2021). Moreover, FDI inflows assist the host economy in obtaining the advantages of the latest technology, management, and communication systems, resulting in increased output and economies of scale inside the country. FDI, on the other hand, has the potential to harm the environment (Canh et al., 2020). The results of the nexus between FDI and CO_2 emissions are mixed. Some of the researchers (Zeraibi et al., 2021) have found that FDI is an important resource of green technology transfer to the economy, which reduces environmental degradation, whereas others have discovered that FDI inflows contribute to boosting environmental degradation since developed countries choose to locate companies in developing economies owing to the accessibility of low-priced resources in general (Ahmad et al., 2020).

This study aims to observe the impact of economic growth and energy consumption in the presence of financial development, urbanization, and FDI inflow for China. According to 2019 data from the Global Carbon Project, China produced the most CO_2 emissions, and its share in the total world CO_2 emissions were around 30.30%. Moreover, China achieves 16.33% of world economic growth (WorldBank, 2021). For this reason, exploring the dynamics of the influence of economic growth and energy consumption on environmental degradation as well as understanding methods to decrease environmental degradation have essential consequences not only for China but also for other countries around the world, because China plays a significant role in the global economy and, in particular, in global CO_2 emissions.

TABLE 1 | Summary statistics.

Variable Name	Unit	Source	Mean	Std. Dev
Environmental degradation (ED)	Metric tons per capita	World Bank	3.791	2.181
Economic growth (EG)	Constant 2010 US dollars	World Bank	2,641.133	2,400.610
Energy consumption (EC)	Kilograms of oil equivalent per capita	World Bank	1,235.354	634.051
Financial development (FD)	% of GDP	World Bank	102.687	31.672
Urbanization	% of the total population	World Bank	36.986	12.889
FDI	% of GDP	World Bank	2.587	1.761

FIGURE 1 | The Proposed Methodology.

TABLE 2 | Unit root test results.

	PP		ADF	
	I (0)	I (1)	I (0)	I (1)
Ln CO_2	−0.280	−3.745***	−0.110	−3.688***
LnEG	−0.473	−2.998**	−0.577	−2.981**
LnEC	0.497	−3.143**	1.076	−3.135**
LnFD	−1.397	−5.846***	−1.357	−5.837***
LnUR	−3.584***	−1.296	−6.184***	−1.127
LnFDI	−9.471***	−18.782***	−13.045***	−19.585***

****, ** denote statistical significance at 1%, 5% level, respectively.*

The main originality of the study is that any study applies the DYNARDL simulations to examine the China case by including the factors in this study and using data between 1979 and 2019. This research contributes to clarifying the impacts of energy consumption, economic growth, financial development, FDI, and urbanization on CO_2 emissions in the literature. This study is critical because China intends to achieve carbon neutrality by 2060. Furthermore, the goal of this study is to fill a substantial knowledge gap, notably in China, and to assist policymakers in developing policies to achieve carbon neutrality in the next 40 years.

After the introduction part, the second part reviews the literature. The third part explains the data and methodology. The fourth part presents the empirical results and discussion. Finally, the fifth part concludes and tells about policy implications.

2 LITERATURE REVIEW

2.1 Economic Growth and CO_2 Emissions Nexus

Numerous researchers in various countries or regions have observed the nexus between economic growth and the environment. The results differ based on the size of the sample and the studied period (Koengkan et al., 2019a; Chishti et al., 2021; Qin et al., 2021). A large number of researchers have used the EKC hypothesis to study the nexus between economic growth and environmental quality (Yilanci and Pata, 2020). The validity of the theory is proved in various countries like the US (Atasoy, 2017), Pakistan (Rehman et al., 2021a), Malaysia (Nurgazina et al., 2021), China (Pata and Caglar, 2021), OECD (Cao et al., 2022).

On the other hand, some studies cannot find the nexus between economic growth and environmental degradation. For instance, Zambrano-Monserrate et al. (2018) analyze the nexus in Peru and find that the results do not support the EKC hypothesis. Another research on South Korea by Koc and Bulus (2020) discovers evidence of an N-shaped link between economic growth and environmental degradation that invalidates the EKC theory. The EKC hypothesis is also invalid in Pakistan according to the findings of Ahmed et al. (2020), where an increase in wealth boosts CO_2 emissions by forming a U-shaped nexus.

The EKC theory, on the other hand, has been supported by multiple studies. For example, Katrakilidis et al. (2016) indicated a positive nexus between economic growth and environmental degradation in Greece. Rauf et al. (2018) revealed in research on the Belt and Road Initiative (BRI) countries that the EKC hypothesis fits all regional panels of the BRI countries. Furthermore, Işık et al. (2019) confirmed the EKC theory in the context of ten states across the United States and concluded that economic growth first increased CO_2 emissions but later reduced them. Many scholars (Zhu et al., 2019) examine the nexus between economic growth and CO_2 emissions in China and found that as the economic level rises, the environmental degradation decreases. Murshed et al. (2021) found support for the EKC hypothesis in the long term in Bangladesh. Likewise, Ahmad et al. (2021) confirmed the EKC for developing countries, as well as the positive environmental benefits of both institutional quality and economic complexity. When including green trade in models, Can et al. (2021) claim that the EKC between environmental deterioration and economic growth persists in OECD countries.

2.2 Energy Consumption and CO_2 Emissions Nexus

A variety of studies have examined the nexus between energy usage and environmental degradation, especially CO_2 emissions (Khan et al., 2021). Bidirectional nexus between these variables has been discovered by certain studies, for example, Pao et al. (2011) identify long-run mutual Granger-causality between energy consumption and environmental degradation in Russia between 1990 and 2007 and suggest that environmental efficiency must be enhanced to decrease pollution. Wasti and Zaidi (2020) determine a mutual causal nexus between energy consumption and environmental degradation in Kuwait. Using the wavelet coherence method, classical Granger, and Toda-Yamamoto causality approaches, Adebayo and Akinsola (2021) discover a bidirectional nexus between environmental degradation and energy consumption in Thailand.

Omri (2013) establishes the presence of positive unidirectional causation between energy consumption and

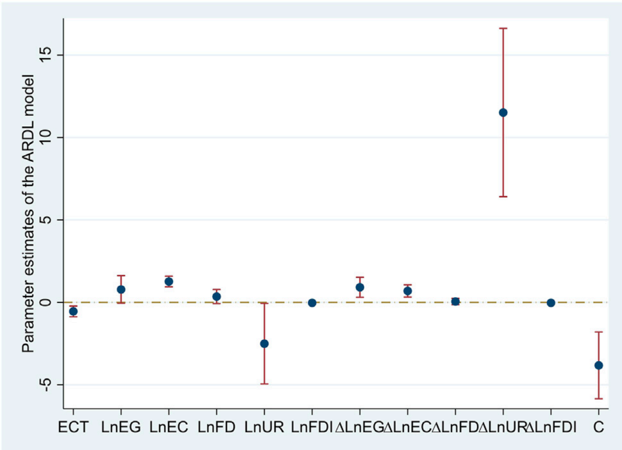

FIGURE 2 | Parameter estimates of the ARDL model. Notes: the estimate in a log-log model is shown by the blue (●), the reference line is represented by the brown teal dash-dot, and the marron-spike represents the lower and upper 95% confidence limit, respectively.

environmental degradation in 14 MENA countries. Furthermore, Ahmed et al. (2017), Aye and Edoja (2017), and Musah et al. (2021) discover energy consumption to be a key booster of CO_2 emissions in five countries of South Asia, 31 emerging nations, and North Africa, respectively. Muhammad (2019) studies the nexus between energy consumption, environmental degradation, and economic growth in the MENA countries by using GMM and SGMM long-term estimations and concludes that an increase in energy consumption causes an increase in environmental degradation in the long run. Using the ARDL bound test approach for Pakistan from 1975 to 2014, Ali et al. (2021) define that fossil energy consumption has a negative influence on environmental degradation. Moreover, Rahman et al. (2021) discover that energy consumption increases the CO_2 emissions of newly industrialized countries between 1979 and 2017 by using Dynamic Ordinary Least Squares (DOLS), Fully Modified Ordinary Least Squares (FMOLS), and Pooled Mean Group (PMG) methods.

On the other hand, Al-Mulali et al. (2015) show that energy usage does not influence CO_2 emissions across Latin America and the Caribbean. Most of the studies, find no impact or positive impact of energy consumption on CO_2 emissions investigate renewable energy. For instance, using disaggregated data for India, Sahoo and Sahoo (2020) evaluate the influence of renewable and nonrenewable energy consumption on environmental degradation and conclude that hydro-energy consumption does not affect the CO_2 emissions, but nuclear electricity consumption reduces CO_2 emissions. Le et al. (2020) reveal that green energy decreases CO_2 emissions in high-income nations using a global panel of 102 economies. Similarly, Ummalla and Goyari (2021) define that using renewable energy reduces CO_2 emissions.

2.3 Evaluation of the Literature

Despite the importance of the topic, there is still a research gap, because numerous studies (Magazzino et al., 2020b; Koengkan and Fuinhas, 2021a; Guo et al., 2022a) in the energy and environmental economics literature apply panel data and time-series analyses to investigate the long-run short-run relation between different variables, however, this research applies the DYNARDL simulations model established by Jordan and Philips (2018) in terms of carbon neutrality in China. This study uses the DYNARDL model to analyze the actual change in the dependent variable in the long and short term by introducing 100% negative shock from explanatory variables. The DYNARDL simulations have the capacity to solve the data's existence issues and interpret the results of the standard ARDL model. While the remaining variables are kept constant, the DYNARDL simulations will approximate and

TABLE 3 | ARDL estimation results.

Variables	Coefficient	Std Err	t	*p*-value	Min 95	Max 95
ECT	–0.548	0.159	–3.44	0.002***	–0.875	-0.220
Long-run						
LnEG	0.784	0.408	1.92	0.066*	–0.054	1.621
LnEC	1.266	0.156	8.13	0.000***	0.946	1.587
LnFD	0.352	0.207	1.70	0.101	–0.074	0.778
LnUR	–2.507	1.189	–2.11	0.045**	–4.951	–0.064
LnFDI	–0.029	0.024	–1.23	0.230	–0.078	0.020
Short-run						
ΔLnEG	0.916	0.297	3.09	0.005***	0.306	1.526
ΔLnEC	0.693	0.183	3.79	0.001***	0.317	1.069
ΔLnFD	0.050	0.094	0.54	0.596	–0.142	0.243
ΔLnUR	11.519	2.483	4.64	0.000***	6.414	16.623
ΔLnFDI	–0.029	0.009	–3.27	0.003***	–0.047	–0.011
C	–3.825	0.987	–3.88	0.001***	–5.853	–1.796
R^2	0.8323	Adj R^2	0.7549	Root MSE	0.0257	

****, **, * denote statistical significance at 1%, 5%, 10% level, respectively.*

TABLE 4 | Stability tests results.

Pesaran, Shin, and Smith Bounds Testing

		10%		**5%**		**1%**		***p*-value**	
	K	**I (0)**	**I (1)**	**I (0)**	**I (1)**	**I (0)**	**I (1)**	**I (0)**	**I (1)**
F	7.065	2.468	3.822	2.995	4.541	4.273	6.272	0.000***	0.005***
t	-3.440	-2.489	-3.797	-2.859	-4.241	-3.616	-5.148	0.015**	0.165

Breusch-Godfrey LM test for autocorrelation

lags(p)	**F**	**df**	**Prob > F**
1	5.872	(1, 25)	0.0230
2	2.989	(2, 24)	0.0693
3	2.101	(3, 23)	0.1279
4	1.933	(4, 22)	0.1406

Cameron and Trivedi's decomposition of IM-test

Source	**chi^2**	**df**	**P**
Heteroskedasticity	39.00	38	0.4246
Skewness	19.35	12	0.0805
Kurtosis	0.33	1	0.5639
Total	58.68	51	0.2146

Skewness/Kurtosis tests for Normality

Variable	**Obs**	**Pr(Skewness)**	**Pr(Kurtosis)**	**Joint adj chi^2 (2)**	**Prob> chi^2**
Residuals	39	0.394	0.9998	0.76	0.685

****, ** denote statistical significance at 1%, 5% level, respectively.*

reflect the predictions of an actual change in the independent variable (Jordan and Philips, 2018).

To study the essential variables' influence on environmental degradation, the study contributes to the literature by including energy consumption, economic growth, financial development, FDI, and urbanization in the CO_2 emission equation. Furthermore, no other researcher has conducted similar research for the China case by using the same factors and for the same period. Therefore, this study can be evaluated as pioneering and significant. Also, this study contributes to the existing literature by providing a clear route for scholars to understand the nexus between selected factors. Moreover, this study assists policymakers of China in developing and implementing strategies to reduce CO_2 emissions to meet the carbon neutrality objective by 2060.

3 DATA AND METHODOLOGY

3.1 Data Description

This study analyses the time series annual data set from 1979 to 2019 for China. Summary statistics are presented in **Table 1**. CO_2 emissions (metric tons per capita) are used as a reference for the environmental degradation in this study. Furthermore, the study employs GDP per capita (constant 2010 US dollars) for the economic growth (EG), energy consumption (EC) is measured in kilograms of oil equivalent per capita, domestic credit to the private sector (% of GDP) represent financial development (FD), urbanization (UR) is measured in % of the total population, FDI shows the net foreign direct investment inflow (% of GDP). The data for the independent and dependent variables are obtained from the World Bank (WorldBank, 2021).

3.2 Model Estimation

There are five stages for the evaluation of the impact of economic growth and energy consumption in the context of financial development, urbanization, and FDI inflow for China as indicated in **Figure 1**.

In the first step, PP and ADF tests are used to identify the order of variable integration. In the second step, the PSS bound test is performed to confirm the presence of long-run cointegration among the variables. In the third step, the ARDL model is employed to identify the short-run and long-run associations between variables. In the fourth step, DYNARDL simulations are estimated. In the fifth step, Kernel-based regularized least squares (KRLS) are utilized to identify the causal association between the variables.

3.2.1 ARDL Model

The environmental degradation function for this study is expressed as:

$$CO_{2t} = f\,(EG_t,\ EC_t,\ FD_t,\ UR_t,\ FDI_t) \quad (1)$$

where, CO_2 represents the environmental degradation, EG represents economic growth, EC is the energy consumption, FD is the financial development, UR is urbanization, FDI is the foreign direct investment in year t. Prior to estimating the model, a logarithmic transformation is performed:

$$lnCO_{2t} = a_0 + a_1 lnEG_t + a_2 lnEC_t + a_3 lnFD_t + a_4 lnUR_t + a_5 lnFDI_t + u_t \quad (2)$$

where, u_t is the error and α_0 displays the constant, α_1, α_2, α_3, α_4, α_5 are the coefficients of the described variables. The ARDL model (Pesaran et al., 2001) used in this study can be expressed as:

$$\begin{aligned}\Delta \ln CO_{2t} = \alpha_0 &+ \sum_{i=1}^{p}\beta_i \Delta \ln CO_{2,t-1} + \sum_{i=1}^{p}\delta_i \Delta \ln EG_{t-1} \\ &+ \sum_{i=1}^{p}\theta_i \Delta \ln EC_{t-1} + \sum_{i=1}^{p}\gamma_i \Delta \ln FD_{t-1} \\ &+ \sum_{i=1}^{p}\vartheta_i \Delta \ln UR_{t-1} + \sum_{i=1}^{p}\rho_i \Delta \ln FDI_{t-1} \\ &+ \lambda_{CO2} \ln CO_{2,t-1} + \lambda_{EG2} \ln EG_{t-1} + \lambda_{EC} \ln EC_{t-1} \\ &+ \lambda_{FD} \ln FD_{t-1} + \lambda_{UR} \ln UR_{t-1} + \lambda_{FDI} \ln FDI_{t-1} + \varepsilon_t \end{aligned} \quad (3)$$

where, $\beta_i, \delta_i, \theta_i, \gamma_i, \vartheta_i, \rho_i$, refer to constant intercepts and λ_{CO2}, λ_{EG}, λ_{EC}, λ_{FD}, λ_{UR}, λ_{FDI} to the long-run coefficients, ε_t is the error term. For short-run correlation analysis, the equation is estimated as shown:

$$\begin{aligned}\Delta\, ln\, CO_{2t} = \alpha_0 &+ \sum_{i=1}^{p}\beta_i \Delta\, ln\, CO_{2,t-1} \\ &+ \sum_{i=1}^{p}\delta_i \Delta\, ln\, EG_{t-1} \sum_{i=1}^{p}\theta_i \Delta\, ln\, EC_{t-1} + \sum_{i=1}^{p}\gamma_i \Delta\, ln\, FD_{t-1} \\ &+ \sum_{i=1}^{p}\vartheta_i \Delta\, ln\, UR_{t-1} + \sum_{i=1}^{p}\rho_i \Delta\, ln\, FDI_{t-1} + \lambda_{ECM} ECM_{t-1} \\ &+ \varepsilon_t \end{aligned} \quad (4)$$

where ECM is the error correction term.

3.2.2 DYNARDL Simulations

The study also performs DYNARDL simulations by Jordan and Philips (2018) to evaluate the counterfactual shock of one factor whereas the others are kept fixed on the dependent variable. Because of the dynamic nature of the data, the model simulation is qualified to assess the impact of positive or negative changes on the independent variables (Sarkodie and Owusu, 2020). The DYARDL model fits an ARDL model in error-correction form and is presented in **Eq. 5**.

$$\begin{aligned}\Delta \ln CO_{2t} = \alpha_0 &+ \sum_{i=1}^{p}\beta_i \Delta \ln CO_{2,t-1} + \sum_{i=1}^{p}\delta_i \Delta \ln EG_{t-1} \\ &+ \sum_{i=1}^{p}\theta_i \Delta \ln EC_{t-1} + \sum_{i=1}^{p}\gamma_i \Delta \ln FD_{t-1} \\ &+ \sum_{i=1}^{p}\vartheta_i \Delta \ln UR_{t-1} + \sum_{i=1}^{p}\rho_i \Delta \ln FDI_{t-1} \\ &+ \lambda_{CO2} \ln CO_{2,t-1} + \lambda_{EG2} \ln EG_{t-1} + \lambda_{EC} \ln EC_{t-1} \\ &+ \lambda_{FD} \ln FD_{t-1} + \lambda_{UR} \ln UR_{t-1} + \lambda_{FDI} \ln FDI_{t-1} \\ &+ \lambda_{ECM} ECM_{t-1} \end{aligned} \quad (5)$$

The DYNARDL model is based on -100% CO_2 emissions (Hepburn et al., 2021) as counterfactual shock over 4 decades, from 2020 to 2060. For parameter vector, the DYNARDL simulations employ 5,000 simulations from a multivariate normal distribution.

3.2.3 KRLS Model

Further, the nexus is investigated using KRLS which employs the pointwise derivatives (Hainmueller and Hazlett, 2014). By eliminating parametric assumptions and enabling a flexible hypothesis, the KRLS model exceeds classic regression analysis and classification issues (Hainmueller and Hazlett, 2014; Ferwerda et al., 2015). As a result, the KRLS model makes it possible to detect potential nonlinearities, interactions, and heterogeneous effects that result in detailed interpretations (Hainmueller and Hazlett, 2014; Hipp et al., 2017).

3.2.4 Model Pre and Post Estimations

Preliminary estimates, including the unit root test, are essential to assess the data's stationarity status to avoid inaccurate findings during analysis. The variables in the ARDL model must be stationary at level I (0), first difference I (1), or a mix of both (Pesaran et al., 2001). The DYNARDL simulations, on the other hand, necessitate the dependent parameter's rigorous first difference stationarity (Jordan and Philips, 2018). The independent variables can be integrated at either level I (0) or first difference I (1), but not higher than I (1).

After satisfying the criteria of rigorous first difference stationarity of the dependent variable, the optimal lag for the proposed model is defined. The cointegration is evaluated using the Pesaran et al. (2001) bounds test with novel Kripfganz and Schneider (2020) critical values and approximate p-values using the optimal lag.

The stability of the models is verified by analysis for serial correlation, normality, heteroscedasticity, and structural breaks. To assess for autocorrelation in the estimated model's residuals, the Breusch-Godfrey LM test is employed. Cameron and Trivedi's decomposition of the IM-test is used to determine residual heteroskedasticity. Skewness/Kurtosis tests are used to determine the independence of residuals. Additionally, both standardized normal probability plots and quantiles of residuals against quantiles of normal distribution estimates support the existence

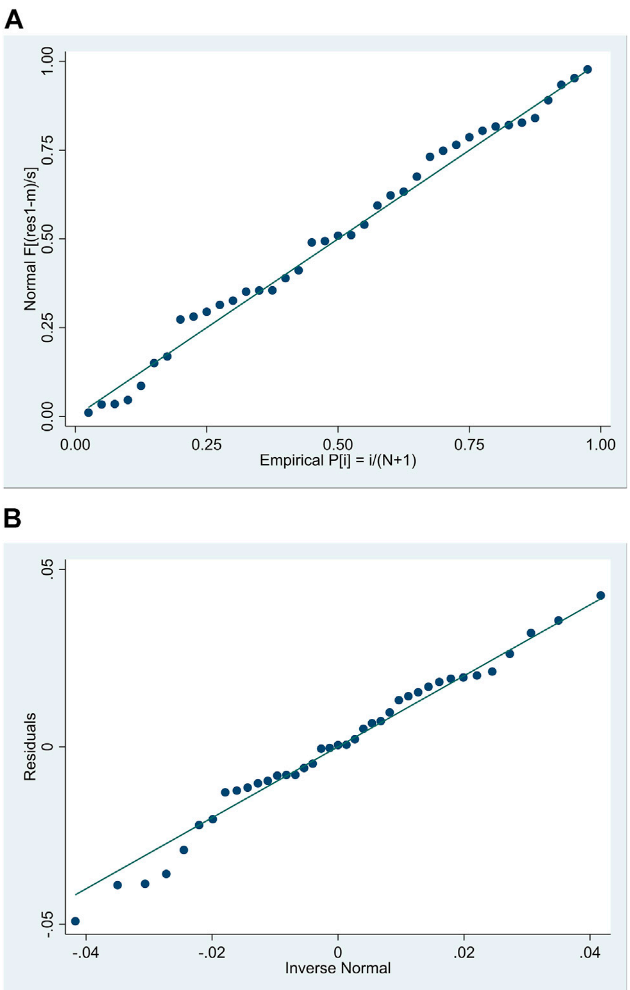

FIGURE 3 | (A) Standardized normal probability plot. **(B)** Quantiles of residuals against quantiles of normal distribution.

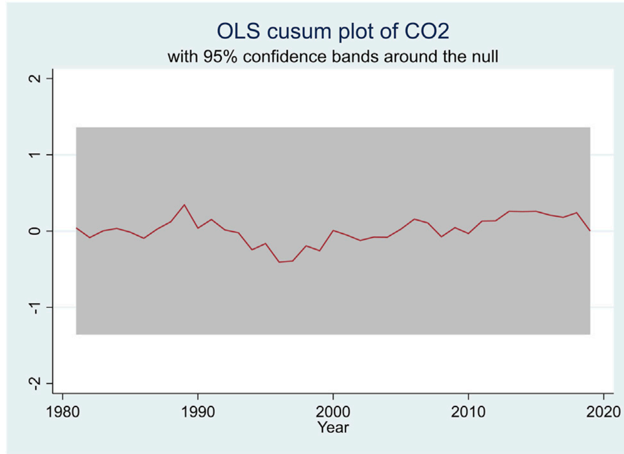

FIGURE 4 | Cumulative sum test using OLS CUSUM plot for parameter stability.

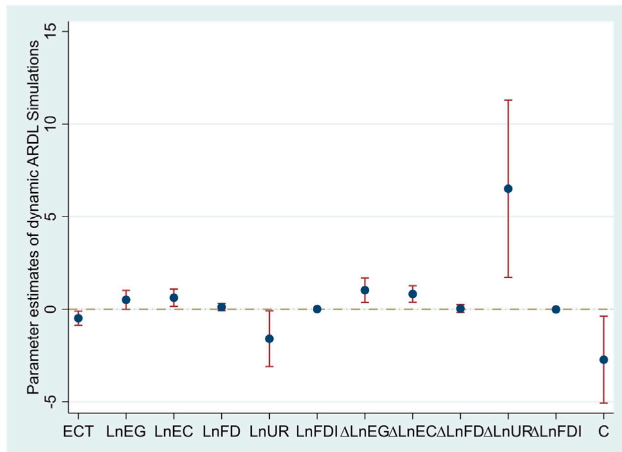

FIGURE 5 | Parameter estimates of DYNARDL simulations. Notes: the estimate in a log-log model is shown by the blue (●), the reference line is represented by the brown teal dash-dot, and the marron-spike represents the lower and upper 95% confidence limit, respectively.

of a normal distribution. Using the cumulative sum test for the stability of variables, possible structural breaks are evaluated.

4 EMPIRICAL RESULTS AND DISCUSSION

4.1 Unit Root Test

To establish the order of integration and produce comprehensive results, the unit root tests are employed for checking the characteristics of the parameters by utilizing PP and ADF tests (Dickey and Fuller, 1981; Perron, 1989). The findings of the unit root tests are shown in **Table 2**.

According to the test results, the ARDL and DYNARDL models can be utilized with the studied variables because the dependent variable is integrated at the I (1) and independent parameters are stationary and integrated at the order I (0) and I (1).

4.2 Estimation of ARDL Model

The lag range (LR) test, final perdition error (FPE), Akaike Information Criteria (AIC), Hannan-Quinn Information Criteria (HQIC), and Schwarz's Bayesian information criterion (SBIC) is used to select the optimal lag for further analysis. The results reveal that the suitable lag is lag 2 (**Appendix 1**).

The results of the ARDL (1, 2, 0, 1, 1, 2) regression are presented in **Figure 2** with its empirical results presented in **Table 3**.

The result of the analysis discloses that economic growth and energy consumption are found to increase environmental degradation in both short-run and long-run analyses. This output aligns with the studies of Fuinhas et al. (2017), Fuinhas et al. (2021), Nawaz et al. (2021), who find the same nexus between energy consumption and CO_2 emissions in 29 European Union Countries, Latin America and BRICS, OECD economies,

TABLE 5 | DYNARDL simulations results.

Variables	Coefficient	Std Err	t	*p*-value	Min 95	Max 95
ECT	−0.484	0.187	−2.59	0.015**	−0.869	−0.100
Long-run						
LnEG	0.508	0.251	2.02	0.053*	−0.007	1.023
LnEC	0.621	0.227	2.73	0.011**	0.154	1.088
LnFD	0.118	0.095	1.23	0.228	−0.078	0.313
LnUR	−1.596	0.735	−2.17	0.039**	−3.104	−0.087
LnFDI	0.010	0.007	1.27	0.214	−0.006	0.025
Short-run						
ΔLnEG	1.027	0.321	3.20	0.004***	0.368	1.687
ΔLnEC	0.820	0.216	3.80	0.001***	0.377	1.263
ΔLnFD	0.038	0.103	0.37	0.718	−0.173	0.248
ΔLnUR	6.508	2.333	2.79	0.010***	1.721	11.296
ΔLnFDI	−0.011	0.026	−0.42	0.681	−0.065	0.043
C	−2.728	1.143	−2.39	0.024**	−5.073	−0.383
R^2	0.7622	Adj R^2	0.6654	Root MSE	0.0301	

****, **, * denote statistical significance at 1%, 5%, 10% level, respectively.*

respectively. Urbanization has a positive impact on CO_2 emissions in the short term, while in the long term increase in the urban population will decrease CO_2 emissions. This is because increasing the compactness of the population will generate economies of scale that improve energy efficiency as well as the efficiency of energy-intensive facilities, thus ultimately reducing CO_2 emissions. Moreover, in addition to economies of scale, population density provides an agglomeration effect that favors technological measures to reduce emissions. This is especially relevant for China, whose population is concentrated in several megapolises, each with more than 20 million people. This result collaborates with the previous studies by Anwar et al. (2020) for Far East Asian Countries. The FDI inflow is only significant in the short-run and negatively affects CO_2 emissions. This result is contrary to the study of Malik et al. (2020), who find that FDI intensifies carbon emissions.

Furthermore, the error correction term (ECT) is negative and significant at less than 5%, indicating that the adjustment speed to the long-run equilibrium will take more than 5 years. Moreover, the R^2 value of 0.8323 indicates that the independent variable can explain 83.23% of the variation in CO_2 emissions.

To examine the long-run cointegration relationship, the ARDL bounds cointegration test (Pesaran et al., 2001) is evaluated by utilizing the novel Kripfganz and Schneider (2020) critical values and approximate *p*-values. The bounds test's results are shown in **Table 4**.

Table 4 illustrates that the F-statistic value of the proposed model is higher than the critical value of the upper bound (4.54) at a 1% level of significance thus there are long-term relationships among variables. Several tests checking autocorrelation, heteroskedasticity normality, and structural breaks are done to ensure the stability of the ARDL model. It can be observed from the result of the Breusch Godfrey LM test that the hypothesis of no serial correlation among variables is accepted at a 5% significance level, which means that residuals are free of serial correlation. Cameron and Trivedi's decomposition of the IM-test shows that the homoscedasticity null hypothesis is accepted at a 5% level of significance, thus the residuals are free from heteroscedasticity. The Skewness/Kurtosis normality tests disclose that the residuals are normally distributed within the mean.

A standardized normal probability plot (**Figure 3A**) and quantiles of residuals against quantiles of normal distribution (**Figure 3B**) are used to further examine the validity of the normality assumption determined by the Skewness/Kurtosis tests.

The residuals based on the ARDL model are normally distributed in both **Figures 3A,B**. Furthermore, the cumulative sum test is used to analyze potential structural breaks that are presented in **Figure 4**.

Figure 4 shows that the assessed t-statistic is within the 95% confidence interval which means the calculated coefficients are stable through the years.

4.3 DYNARDL Simulations

Figure 5 shows the variable graph of the DYNARDL, while **Table 5** shows its empirical estimation.

The results of the long and short-run simulations illustrate that economic growth will increase CO_2 emissions. This output aligns with the studies of Koengkan et al. (2019b), Malik et al. (2020), Zhang et al. (2021), Rehman et al. (2022). Moreover, growth in energy consumption will worsen the environmental situation. Our result is consistent with numerous studies conducted in various countries such as Khan et al. (2020) in Pakistan, Ummalla and Goyari (2021) in BRICS countries, Adebayo (2021) in Indonesia, Martins et al. (2021) in G7 countries, and Pata and Kumar (2021) in China. Financial development has no impact on environmental degradation.

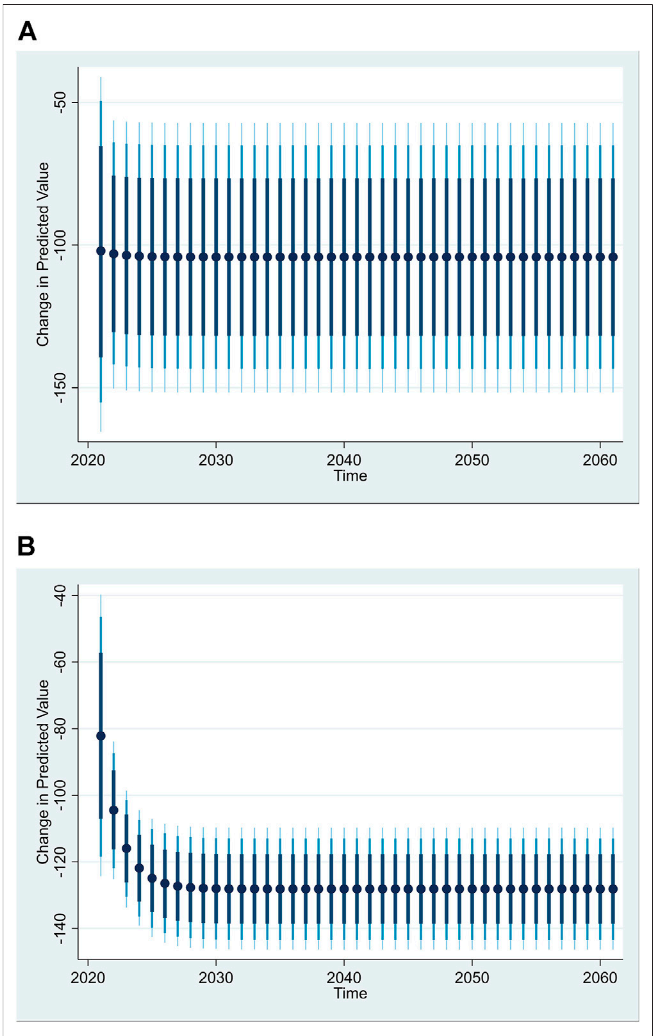

FIGURE 6 | Representation of counterfactual shock in forecast variables employing the DYNARDL model: **(A)** economic growth: **(B)** energy consumption. Note: dark navy dot (●) represent the forecast emissions by −100% shocks in a log-log model; navy teal, bright blue, and light-blue spikes show 75%, 90%, and 95% confidence bands.

TABLE 6 | Pointwise derivatives using KRLS.

CO_2	Avg	SE	t	P > *t*	P-25	P-50	P-75
EG	0.117	0.009	13.738	0.000***	0.076	0.099	0.180
EC	0.275	0.018	14.965	0.000***	0.105	0.182	0.461
FD	−0.016	0.039	−0.397	0.694	−0.174	−0.015	0.081
UR	0.249	0.020	12.646	0.000***	0.097	0.169	0.441
FDI	0.028	0.007	4.046	0.000***	0.003	0.031	0.051
Lambda	0.106	Sigma		5.000	R^2	0.997	
Tolerance	0.041	Eff. Df		9.582	Looloss	0.913	

****, **, * denote statistical significance at 1%, 5%, 10% level, respectively.*

Urbanization will improve the environmental situation in the long run, while in the short-run growth in the urban population will increase CO_2 emissions.

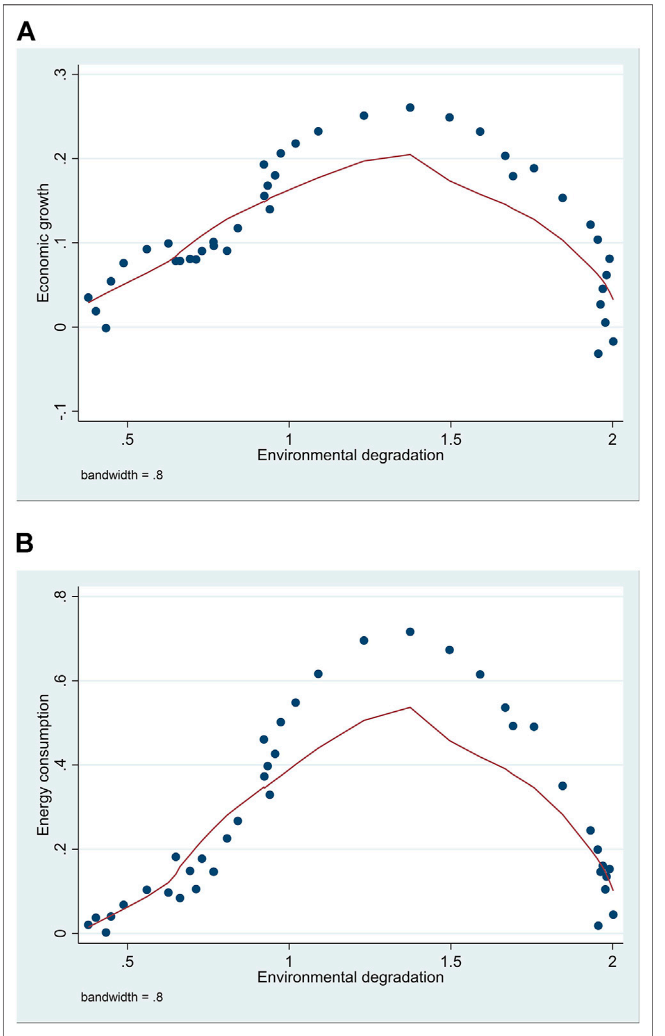

FIGURE 7 | Representation of Pointwise marginal effect: **(A)** of economic growth; **(B)** of energy consumption.

Moreover, the estimated ECT of -0.484, which is significant at a 5% level indicates the long-run cointegration between economic growth, energy consumption, financial development, urbanization, FDI inflow, and environmental degradation. Moreover, the R^2 value of 0.7622 indicates that the explanatory factors can explain 76.22% of the variation in CO_2 emissions.

In general, both the ARDL and DYNARDL estimates suggest that China's economic development and energy consumption have a detrimental impact on the environment. The DYNARDL simulation is based on carbon neutrality by 2060 (Mallapaty, 2020; Hepburn et al., 2021; Ren et al., 2021). The simulation results are presented in **Figure 6**.

The plots presented in **Figure 6** expose that -100% of shocks in the estimated economic growth do not affect environmental degradation, while the same shocks in the calculated energy consumption boost CO_2 emissions in the first 5 years and stabilize in the long run.

4.4 Kernel-Based Regularized Least Squares

A machine learning KRLS approach is employed to check and identify the relationships among the variables to additional enhance the results of this study and the results are presented in **Table 6**.

Table 6 shows that the general model's predictive power is 0.997 meaning that descriptive factors explain 99.7% of the variation in CO_2 emissions. The average pairwise marginal effect of economic growth, energy consumption, financial development, urbanization, and FDI inflow are 0.12%, 0.28%, -0.02%, 0.25%, and 0.03%, respectively. Except for financial development, the probability value of every parameter at a 1% level of significance indicates that there is evidence of a causal-effect correlation. The long-term impacts of economic growth and energy consumption fluctuation as well as their influence on carbon emissions are also investigated by plotting the pointwise derivative that is presented in **Figure 7**.

The marginal impact of economic growth and energy consumption on environmental degradation represented in **Figure 6** shows that the increasing level of economic growth and energy consumption raise CO_2 emissions until they reach a limit where growing marginal returns occur, but then economic growth and energy consumption decrease when CO_2 emissions increase. Thus, economic growth and energy consumption have declining marginal returns with growing CO_2 emissions.

5 CONCLUSION AND POLICY RECOMMENDATION

This study examines the impact of economic growth and energy consumption on the CO_2 emissions in the presence of financial development, urbanization, and FDI inflow for China. The results of the ARDL and DYNARDL in the long-run and short-run illustrate that economic growth will increase environmental degradation. Moreover, growth in energy consumption will increase CO_2 emissions. Urbanization will improve the environmental situation in the long run, while in the short-run rise in urban population will increase carbon emissions. The DYNARDL model shows that a decrease in energy consumption will affect CO_2 emissions in the first 5 years, while economic growth has no impact on CO_2 emissions. The KRLS approach shows that economic growth and energy consumption have declining marginal returns with growing CO_2 emissions.

Our findings have far-reaching ramifications. Firstly, to address environmental issues, the monitoring and control of carbon emissions should be strengthened, and multiple solutions, such as accelerating economic reconstruction, reducing fossil energy consumption, and encouraging environment-friendly energy consumption, should be designed to address carbon emissions and the resulting problems. In addition, renewable energy should be used to minimize dependency on insecure energy infrastructure and maintain energy security in specific high-energy-consumption industries such as manufacturing, transportation, housing, and others. Furthermore, authorities must establish tax exemptions for renewable energy so that companies may quickly switch from fossil fuel to renewable energy.

Secondly, to slow climate change and reduce the adverse effects of carbon emissions on China's economy, the government should rigorously implement the low carbon emission reduction policy and speed up the economic transition to an environmentally friendly growth pattern.

Moreover, to support the environment, the government must focus on increasing the environmental effect of ecological innovation. As a result, authorities should make a concerted effort to encourage environmental innovations to promote green policies. Environmental and social challenges must be addressed while encouraging long-term economic growth via green innovation and technology policy. Setting standards to identify environmental requirements for technology that might enhance environmental quality is also essential. Environmental innovation creates a platform that allows businesses to exchange innovative technologies and benefits while also encouraging cooperation.

Even though this study determines a link between energy consumption, economic growth, FDI, urbanization, and CO_2 emissions, it also has several shortcomings. The findings of this study also indicate that more investigation using various statistical models is required. This research only focused on energy consumption and economic growth, leaving out renewable and nonrenewable energy consumption as well as green technologies. As a result, it is important to include these variables in future studies because renewable energy consumption and green technologies can assist to cut carbon emissions and attain carbon neutrality.

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

ZN: Conceptualization, Data curation, Formal analysis, Methodology, Writing—original draft; QG: Funding acquisition, Project administration, Supervision; UA: Writing—review and editing; MTK: Writing—review and editing; AU: Writing—review and editing; ZAK: Writing—review and editing.

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APPENDIX 1

Lag Length Selection Criteria

Lag	LL	LR	FPE	AIC	HQIC	SBIC
0	251.516		0.000	−18.809	−18.711	−18.470
1	510.274	517.520	0.000	−34.944	−34.164	−32.234
2	617.581	214.610*	0.000*	−39.429*	−37.966*	−34.349*

** indicates the lag order selected by criteria.*