

Environmental Sustainability and Economic Development in Central Asia: The Role of Energy, Trade, and Foreign Investment

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This study investigates the relationship between carbon dioxide (CO₂) emissions, economic growth, energy consumption, foreign direct investment, and trade openness in Kazakhstan, the Kyrgyz Republic, and Uzbekistan over the period 1997–2024. Using panel data from the World Bank and applying the Pooled Mean Group estimator within a panel Autoregressive Distributed Lag framework, the analysis examines both short-run and long-run dynamics among the variables. The results reveal a long-run equilibrium relationship between carbon emissions and their key economic determinants. Energy consumption, foreign direct investment, and trade openness are found to increase CO₂ emissions in the long run, while economic growth contributes to environmental improvement. The findings highlight the dominant role of energy use in driving emissions and the environmental implications of investment and trade integration. These results suggest that Central Asian economies should promote renewable energy, enhance energy efficiency, and adopt environmentally sustainable investment and trade policies to achieve balanced economic growth and environmental sustainability.

Keywords: energy, CO₂, economic growth, trade openness, Central Asia

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Introduction

The challenge of ensuring sustainable economic growth and preserving environmental quality has emerged as one of the most urgent tasks for developed and developing countries alike (Karimov et al. 2025a; Sun et al. 2025). Countries around the world have increasingly focused their economic policies on ensuring sustainable economic growth (Sobirov, Jeong et al. 2023; Polat and Çil 2025). Economic growth has also been identified as a factor that has contributed to climate change and global warming, which have been identified as among the most serious global challenges (Koirala et al. 2025). The increase in carbon dioxide (CO₂) and other greenhouse gases is mainly attributed to industrialization and urbanization (Ahmad et al. 2016). As the leading cause of greenhouse gas emissions, CO₂ has been identified as playing a central role in environmental sustainability and climate change policies (Gibba et al. 2024; Wang et al. 2024). The identification of the determinants of CO₂ emissions is therefore important for the formulation of policies that can ensure a balance between economic growth and environmental sustainability.

The large body of research literature that has explored the relationship between CO₂ emissions, energy consumption, and economic growth has generally indicated that energy is a basic input in production that is similar to land, labour, capital, and entrepreneurship (Ozcan and Ozturk 2019; Koirala et al. 2025; Gahlot and Garg 2025). Energy has been identified as an essential and non-substitutable resource that is central to economic activity, meaning that production activities are directly affected by energy consumption patterns (Ghali and El-Sakka 2004). CO₂ emissions are therefore influenced by economic growth and energy consumption intensity (Kasman and Duman 2015). The growing energy demand is inextricably linked with the course of development of emerging economies, in which the process of industrialization and infrastructure development is often heavily dependent on fossil fuels (Koirala et al. 2025). Despite extensive empirical research, the evidence remains inconclusive and varies across countries and regions (Abdurakhmanova et al. 2022; Jeong et al. 2023a; Ozcan and Ozturk 2019; Shahbaz et al. 2013), highlighting the importance of context-specific analysis, particularly for transition economies such as those in Central Asia (Syzdykova and Azretbergenova 2021).

The above-mentioned problems are especially significant for transition economies, such as Central Asia and the Commonwealth of Independent States, in which countries have varying levels of development, energy

consumption, and resource endowment. In many transition economies, energy consumption is often heavily dependent on energy-intensive sectors to promote economic growth, and thus the relationship between energy consumption and environmental degradation is of particular significance (Kurmanov et al. 2025). On the other hand, foreign direct investment and trade openness have grown considerably, which could have an impact on environmental outcomes (Sobirov, Jeong et al. 2023). Foreign direct investment can lead to an increase in emissions due to pollution-intensive production or a decrease in emissions due to technology transfer and efficiency gains. Likewise, trade openness can have an impact on environmental quality through the effects of scale, composition, and technique (Wang et al. 2024).

Despite the growing attention to the nexus of energy, growth, and the environment, there is still a lack of empirical support for Central Asian economies (Sobirov, Tukhtamurodov et al. 2023; Jeong et al. 2023b; Yul-doshboy et al. 2025). Kazakhstan, the Kyrgyz Republic, and Uzbekistan have undergone significant economic transformation, accompanied by growing energy demand, foreign direct investment, and trade integration (Karimov et al. 2025a). However, these countries are still heavily reliant on fossil fuels and energy-intensive production structures, which poses a threat to environmental sustainability. There is still a lack of empirical research that investigates the joint impact of energy consumption, economic growth, foreign direct investment, and trade openness on CO₂ emissions in Central Asia.

This study makes several important contributions to the existing literature on the energy–growth–environment nexus in Central Asia. First, it provides a comprehensive empirical analysis by jointly examining the effects of economic growth, energy consumption, foreign direct investment, and trade openness on CO₂ emissions within a unified framework, whereas most previous studies have focused on a limited set of variables. Second, the study uses updated data covering the period 1997–2024, offering more recent evidence for transition economies in Central Asia. Third, the study applies the panel Autoregressive Distributed Lag (ARDL) model using the Pooled Mean Group (PMG) estimator, which allows for the distinction between short-run and long-run dynamics while accounting for cross-country heterogeneity. Finally, the study contributes to the literature by providing policy-relevant insights on how economic growth and globalization factors influence environmental sustainability in resource-dependent economies, thereby extending the existing em-

pirical evidence for Kazakhstan, the Kyrgyz Republic, and Uzbekistan. Moreover, the findings of this study are expected to help policymakers design effective policies to support sustainable economic growth, enhance energy efficiency, and improve environmental protection.

To achieve the objectives of the study, this paper addresses the following research questions. First, what are the long-run elasticities between carbon dioxide emissions and their key determinants, namely economic growth, energy consumption, foreign direct investment, and trade openness, in Central Asian economies? Second, how do short-run dynamics influence carbon emissions, and how quickly do deviations from long-run equilibrium adjust over time? Third, what is the direction of causality among these variables? The ARDL model with PMG estimator is particularly suitable for addressing these questions, as it allows for the estimation of both long-run equilibrium relationships and short-run adjustments while accounting for cross-country heterogeneity. In addition, the inclusion of the error correction mechanism enables the analysis of the speed of adjustment, and the panel Granger causality test provides further insights into the direction of relationships among the variables.

This article is structured into five sections. Following the introduction, the second section provides a comprehensive review of the theoretical and empirical literature on the relationship between carbon emissions, economic growth, energy consumption, foreign direct investment, and trade openness. The third section describes the data sources, variable definitions, and econometric methodology employed in the study. The fourth section presents and discusses the empirical findings. The final section concludes by summarizing the main results, outlining policy implications, and suggesting avenues for future research.

Literature Review

This section reviews the existing literature on the relationship between energy consumption, economic growth, and environmental sustainability.

The existing literature indicates that a considerable amount of work has been done on the inter-linkages between carbon dioxide emissions, foreign direct investment, energy consumption, and economic development (Sobirov, Tukhtamurodov et al. 2023; Gahlot and Garg 2025; Patel and Samal 2026). However, empirical studies that exclusively focus on Kazakhstan, the Kyrgyz Republic, and Uzbekistan are still relatively limited (Sobirov, Tukhtamurodov et al. 2023; Karimov et al. 2025a). A great deal of literature has explored the energy–growth–environment nexus

in different regions, employing different econometric models and datasets to study the inter-linkages between these variables (Padhan and Bhat 2025; Wong 2025).

Recent empirical studies have highlighted the strong link that exists between energy consumption and environmental degradation. For example, Muhammad (2019) analysed the linkages that exist between energy consumption, carbon emissions, and economic growth using a panel of 68 countries through the application of dynamic regression techniques such as system generalized method of moments, generalized method of moments, and seemingly unrelated regression. The results show that the augmentation of energy use leads to an increase in carbon emissions, thereby complementing economic growth. Likewise, recent autoregressive distributed lag studies have found that energy use is still a significant factor in determining carbon emissions in developed and developing countries, although the magnitude of its effect varies according to regional and development factors (Lojanica et al. 2025). Mehmood et al. (2021) used quarterly data from 1996 Q1 to 2016 Q4 and applied an ARDL approach to investigate the case of Bangladesh, India, and Pakistan to analyse the influence of institutional quality, economic development, renewable energy, and foreign investment on carbon emissions. In a related study, Magazzino (2016) employs a panel vector autoregression (PVAR) approach to investigate the dynamic interactions among GDP, energy consumption, and CO₂ emissions in the South Caucasus and Turkey. The findings highlight the presence of strong interdependencies and feedback relationships among these variables, emphasizing the importance of considering dynamic linkages in environmental analysis. The findings show that better institutions and higher levels of GDP help to reduce carbon emissions.

The environmental Kuznets Curve hypothesis remains one of the core assumptions in the current empirical work (Wang et al. 2025; Phiri and Raimi 2025; Wong 2025). Current studies examine the extent to which economic development initially increases environmental stress but eventually results in improvements once a threshold income is attained (Binh et al. 2025; Adekunle 2025; Karimov 2026). The link between energy consumption and economic development also differs from one country to another due to structural and development factors. Consequently, empirical results remain mixed on the nature of the causal link between energy consumption and economic development. There are four major theoretical approaches that describe this relationship: the growth, con-

servation, neutrality, and feedback theories (Akadiri et al. 2019). The growth hypothesis argues that increased economic activities lead to an increase in energy demand, which implies that energy constraints can hamper economic growth (Patel and Samal 2026). On the other hand, the conservation hypothesis argues that economic growth is driven by energy consumption, which indicates that policies to control energy consumption can have little effect on economic growth (Kurmanov et al. 2025; Gahlot and Garg 2025). The feedback hypothesis argues that economic growth and energy consumption are related in both directions, while the neutrality hypothesis argues that there is no significant relationship between economic growth and energy consumption (Apergis and Payne 2010). Other studies emphasize the significance of technological advancements, the use of renewable energy sources, and structural changes in determining the relationship between economic growth and environmental quality (Shahzadi et al. 2022; Aidoo 2024). These studies suggest that economic growth alone is not enough to ensure environmental improvement without technological advancements and energy transformation (Wang et al. 2025; Padhan and Bhat 2025).

Findings from studies focusing on developing and transition economies can also offer additional information on the relationships between energy consumption, foreign investment, and economic performance (Adekunle 2025). Umurzakov et al. (2020) used panel cointegration and panel dynamic ordinary least squares analysis to investigate the short- and long-run relationships between energy production and economic growth in post-communist countries from 1995 to 2014. The findings support the existence of a long-run equilibrium relationship between energy consumption and economic growth. Solarin and Ozturk (2015) used vector autoregression, generalized least squares, and Johansen cointegration tests to investigate the role of hydropower energy consumption in economic growth in seven Latin American countries. The study found that hydropower energy consumption has a positive effect on economic growth. Similarly, Inglesi-Lotz (2016) found that the consumption of renewable energy has a positive effect on economic growth in OECD countries.

Foreign direct investment (FDI) has been acknowledged as a factor that affects economic performance and environmental conditions (Sobirov, Jeong et al. 2023; Adekunle 2025; Binh et al. 2025). Recent panel ARDL tests have shown that FDI and trade openness are important factors in determining emissions and environmental quality in developing countries (Mebrek et al. 2024). Abdouli and Hammami (2017) used a

growth model and a generalized method of moments equation to examine the relationship between economic growth, foreign investment, and energy consumption in Middle Eastern and North African countries, finding that there is a two-way relationship between economic growth and FDI and between economic growth and energy consumption. Moreover, Muhammad and Khan (2019) also found that FDI inflows and energy consumption play a significant role in supporting economic development in Asian economies.

In addition, various empirical studies have emphasized the environmental impacts of foreign investment, urbanization, and trade liberalization (Hadili et al. 2025). Li et al. (2022) investigated the relationships between urbanization, FDI, energy consumption, and carbon emissions in emerging economies through the application of econometric models that consider cross-sectional dependence and heterogeneity. The findings indicate that urbanization and energy consumption are significant contributors to emissions, while foreign investment can be a mitigating factor through technological advancements. Islam et al. (2021) applied dynamic ARDL simulations on Bangladesh and found that globalization, innovation, and foreign investment are significant factors in reducing emissions, while urbanization, energy consumption, and trade increase emissions in both the short and long terms.

Trade openness has also been recognized as a significant factor in determining environmental quality (Sobirov, Tukhtamurodov et al. 2023). Ansari et al. (2020) applied a vector error correction model and Granger causality tests to assess the role of energy consumption, trade openness, and economic growth in affecting carbon emissions in the world's largest emitters. The results confirmed the existence of a long-run relationship between emissions and economic factors, emphasizing the role of trade and energy consumption in determining environmental factors.

In addition to traditional econometric approaches, recent studies have increasingly applied machine learning (ML) techniques to analyse the relationships between energy consumption, economic growth, and environmental sustainability (Magazzino and Mele 2025; Manuguerra et al. 2026). For instance, Magazzino et al. (2021) use machine learning methods to examine the relationships among renewable energy production, coal consumption, economic growth, and CO₂ emissions, showing that greater reliance on renewable energy can contribute to emission reductions. In another study, Manuguerra et al. (2025) develop a parametric ML model to estimate the energy consumption of manufacturing com-

ponents during the conceptual design phase, enabling faster evaluation of energy efficiency implications in industrial production. These studies highlight that ML-based approaches can capture complex relationships and provide predictive insights that complement traditional econometric techniques. Nevertheless, econometric techniques such as panel ARDL remain widely used because they allow clear interpretation of both short-run and long-run relationships and provide important policy insights.

Notwithstanding the vast body of international literature on the energy–growth–environment nexus, studies specifically concentrating on the Central Asian states are still scarce (Kurmanov et al. 2025; Karimov et al. 2025a). In particular, prior research has mainly examined individual relationships, such as energy consumption and economic growth or trade and emissions, rather than integrating multiple economic drivers within a single empirical framework. In addition, only a few studies have used recent data and econometric approaches that allow for distinguishing between short-run and long-run dynamics in these transition economies (Hadili et al. 2025; Patel and Samal 2026). To address the research gap, the current study examines the short- and long-run relationships between carbon emissions, energy consumption, economic growth, foreign direct investment, and trade openness for Kazakhstan, the Kyrgyz Republic, and Uzbekistan during the period from 1997 to 2024. Using a panel autoregressive distributed lag approach, this study provides novel empirical evidence on the determinants of environmental degradation and sustainable economic development in the transition economies of Central Asia.

Data and Methodology

This section introduces the data sources, variables, and econometric techniques employed in the analysis of the interrelationship between carbon dioxide emissions, economic growth, energy use, foreign direct investment, and trade openness in the Central Asian economies. The study will concentrate on Kazakhstan, the Kyrgyz Republic, and Uzbekistan, which are transition economies that are characterized by rising energy demand, growing international trade, and rising foreign investment flows. It is important to comprehend the dynamic relationships between these variables in order to assess the environmental consequences of economic development.

This study employs data based on annual observations from 1997 to 2024. The data is collected from the World Bank's World Development Indicators to ensure consistency in the data. Carbon dioxide emissions

are chosen as the indicator of environmental pressure and are the dependent variable in the empirical study. Economic growth, energy use, trade openness, and foreign direct investment are chosen as the major explanatory variables because of their significant role in economic development and environmental pressures.

The variables of the study, along with their definitions, measurement methods, and corresponding data sources, are summarized in table 1. Environmental degradation is measured by carbon dioxide emissions as the dependent variable. Economic performance is measured by gross domestic product in constant 2015 US dollars (absolute values), while energy consumption represents the magnitude of energy use driven by production and economic activities. Trade openness is measured by the ratio of total exports and imports to GDP, which shows the degree of engagement in the global economy, while foreign direct investment is measured by net inflows of foreign capital. Generally, increased energy use and trade openness are expected to accentuate carbon emissions, while the effect of economic growth and foreign investment might be sensitive to technological advancements and development levels. All variables are extracted from the World Development Indicators and converted to logarithmic terms to improve consistency and facilitate interpretation.

TABLE 1 Description of Variables and Data Sources

Variable	Definition	Measurement	Data Source
CO ₂ emissions (lnco2)	Carbon dioxide emissions represent the level of environmental degradation and are used as the dependent variable in the model.	Metric tons per capita (logarithmic form)	World Bank (2025), World Development Indicators
Economic growth (lngdp)	Economic growth is represented by real GDP, which reflects the overall scale of economic activity and development.	GDP (constant 2015 US dollars, absolute value), logarithmic form	World Bank (2025), World Development Indicators
Energy consumption (lnenergy)	Energy use measures the level of energy consumption associated with production and economic activity.	Energy use per capita (kg of oil equivalent), logarithmic form	World Bank (2025), World Development Indicators
Trade openness (lntrade)	Trade openness captures the degree of integration into the global economy through exports and imports.	Sum of exports and imports as percentage of GDP, logarithmic form	World Bank (2025), World Development Indicators
Foreign direct investment (lnfdi)	Foreign direct investment reflects cross-border investment flows that may influence industrial activity and technology transfer.	Net FDI inflows (BoP, current US dollars), logarithmic form	World Bank (2025), World Development Indicators

Moreover, the research uses the Pooled Mean Group method in the panel Autoregressive Distributed Lag model to analyse the short-run and long-run relationships between carbon emissions, economic growth, energy use, trade openness, and foreign direct investment. The method allows for the cross-country differences in the short-run adjustment processes while imposing the equality of the long-run parameters on the panel, which is relevant for the analysis of transitional economies. The approach provides a robust way of determining the equilibrium relationships.

The basic empirical model for the analysis is specified as follows:

$$\ln co2_{it} = \beta_1 \ln gdp_{it} + \beta_2 \ln energy_{it} + \beta_3 \ln trade_{it} + \beta_4 \ln fdi_{it} + \varepsilon_{it}. \quad (1)$$

In specification (1), $\ln co2_{it}$ denotes carbon dioxide emissions. The term $\ln gdp_{it}$ represents the natural logarithm of gross domestic product measured in constant 2015 US dollars and is included as a key macroeconomic indicator capturing the overall scale of economic activity. The variable $\ln energy_{it}$ refers to energy use, while $\ln trade_{it}$ indicates the degree of trade openness. Furthermore, $\ln fdi_{it}$ corresponds to net inflows of foreign direct investment recorded in current US dollars according to the balance of payments framework. Finally, ε_{it} signifies the stochastic disturbance term.

Before proceeding to estimate the ARDL model, it is important to test for the presence of unit roots and cointegration. The ARDL model is especially suited for small samples and allows for easy distinction between the short-run and long-run behaviour of the variables. The model is also capable of handling data that spans a large time period. According to Pesaran et al. (1997), the long-run coefficients derived from this model are super-consistent, whereas the short-run coefficients converge at the rate of $\sqrt{T}$. Accordingly, Equation (1) is reformulated into a panel ARDL (p, q_1, q_2, q_3, q_4) structure, where p denotes the number of lags of the dependent variable and each q represents the lag lengths of the explanatory variables. The general representation of the panel ARDL model can therefore be written as follows:

$$\begin{aligned} \ln co2_{it} = & \alpha_i + \sum_{j=1}^p a_{1,ij} \ln co2_{i,t-j} + \sum_{j=0}^{q_1} a_{2,ij} \ln gdp_{i,t-j} + \sum_{j=0}^{q_2} a_{3,ij} \ln energy_{i,t-j} \\ & + \sum_{j=0}^{q_3} a_{4,ij} \ln Trade_{i,t-j} + \sum_{j=0}^{q_4} a_{5,ij} \ln fdi_{i,t-j} + \varepsilon_{it}. \end{aligned} \quad (2)$$

Here, $i = 1, 2, 3, \dots, N$ denotes the cross-sectional units, while $t = 1, 2, 3, \dots, T$ represents the time dimension. The term α_i captures the country-specific fixed effects. The parameters a_1 through a_5 correspond to the estimated coefficients of the explanatory variables and associated regressors, reflecting their interrelated movements over the specified period. The disturbance component ε_{it} represents a white-noise error term that varies across both countries and time.

The panel error correction model (ECM) form derived from Equation (3) can be expressed as follows:

$$\begin{aligned} \ln co2_{it} = & \alpha_i + \sum_{j=1}^p a_{1,ij} \ln co2_{i,t-j} + \sum_{j=0}^{q_1} a_{2,ij} \ln gdp_{i,t-j} + \sum_{j=0}^{q_2} a_{3,ij} \ln energy_{i,t-j} \\ & + \sum_{j=0}^{q_3} a_{4,ij} \ln Trade_{i,t-j} + \sum_{j=0}^{q_4} a_{5,ij} \ln fdi_{i,t-j} + \beta_{1,ij} \ln co2_{i,t-1} \\ & + \beta_{2,ij} \ln gdp_{i,t-1} + \beta_{3,ij} \ln energy_{i,t-1} + \beta_{4,ij} \ln trade_{i,t-1} \\ & + \beta_{5,ij} \ln fdi_{i,t-1} + \varepsilon_{it}. \end{aligned} \quad (3)$$

The panel error correction model captures both short-run dynamics and long-run relationships between CO₂ emissions and its determinants. The coefficients a_1 to a_5 represent short-run effects of past values of emissions, economic growth, energy consumption, trade openness, and foreign direct investment. The coefficients β_1 to β_5 reflect long-run relationships, indicating how these variables influence CO₂ emissions over time. The country-specific term α_i accounts for unobserved heterogeneity, while the error term ε_{it} captures random shocks.

The existence of long-term equilibrium relationships between the dependent variable and the explanatory factors is specified within the panel error correction model presented in Equation (4).

$$\begin{aligned} \ln \Delta co2_{it} = & \alpha_i + \sum_{j=1}^p a_{1,ij} \ln \Delta co2_{i,t-j} + \sum_{j=0}^{q_1} a_{2,ij} \ln \Delta gdp_{i,t-j} \\ & + \sum_{j=0}^{q_2} a_{3,ij} \ln \Delta energy_{i,t-j} + \sum_{j=0}^{q_3} a_{4,ij} \ln \Delta trade_{i,t-j} \\ & + \sum_{j=0}^{q_4} a_{5,ij} \ln \Delta fdi_{i,t-j} + \theta_i ECM_{i,t-1} + \varepsilon_{it}. \end{aligned} \quad (4)$$

In this formulation, the symbol Δ indicates that the variables are expressed in first differences. The parameters a_1 through a_5 represent the estimated short-term effects. In contrast, the coefficients β_1 to β_5 capture

the long-run elasticities associated with carbon emissions, economic expansion, energy usage, trade integration, and foreign direct investment, respectively. Moreover, θ_i denotes the coefficient associated with the error correction term (ECM), reflecting the rate at which deviations from the long-run equilibrium are corrected on an annual basis. Given the relatively small number of yearly observations, a maximum lag length of three is adopted for the ECM specification. The selection of this optimal lag structure is based on the Akaike Information Criterion (AIC).

The panel ARDL model is estimated using the Pooled Mean Group (PMG) approach developed by Pesaran et al. (1997). This approach combines the pooling and averaging steps for cross-sectional units, allowing for differences in intercepts, short-run coefficients, and error variances while assuming that long-run coefficients are homogeneous across countries. Under the assumption of long-run homogeneity, the PMG approach provides consistent and reliable estimates of long-run relationships. In addition, when the number of cross-sectional units is relatively small, as in the case of this study, the PMG estimator is more robust to outliers and can assist in dealing with problems of serial correlation. The likelihood-based estimation method also assists in overcoming possible endogeneity problems by identifying appropriate lag lengths for both dependent and independent variables.

Before proceeding to the estimation of the main panel model, it is necessary to check the stationarity properties of the variables. To test the existence of unit roots in the panel data set, this study uses the Im et al. (2003) test and the Fisher-type test developed by Maddala and Wu (1999). Both tests are based on the augmented Dickey-Fuller (ADF) approach for panel data and can be written in the following general form:

$$\Delta y_{it} = \alpha_i \gamma_i y_{it-1} + \sum_{j=1}^p \phi_j \Delta y_{i,t-1} + \varepsilon_{it}, \quad (5)$$

where $\gamma_i = \rho_i - 1$.

Both procedures examine the null hypothesis of a unit root, stated as $\gamma_i = 0$ (equivalently $\rho_i = 1$), against the alternative hypothesis that the series is stationary, expressed as $\gamma_i < 0$ (or $\rho_i < 1$).

Table 2 summarizes the variables used in the empirical model and outlines their key features. Due to data limitations, the maximum number of observations that can be used is 75. A total of five variables are used in the model, of which one is the dependent variable, and the other four are ex-

TABLE 2 Descriptive Statistics

Variable	Obs	Mean	Std. dev.	Min	Max
lnco2	68	1.366584	0.9236011	-0.2196311	2.730512
lngdp	75	24.22159	1.431896	21.87145	26.09241
lnfdi	72	20.41342	1.85864	15.35495	23.56956
lntrade	75	4.325496	0.3630004	3.373905	4.984333
lnenergy	63	0.4851469	0.7653352	-0.8303974	1.589235

planatory variables. The sample covers Kazakhstan, the Kyrgyz Republic, and Uzbekistan over the period 1997–2024. Due to data availability constraints, the panel is unbalanced, and the number of observations varies across countries and variables, as reflected in tables 2 and 3. In general, lower values are more frequently associated with the Kyrgyz Republic, while higher values are typically observed for Kazakhstan, reflecting differences in economic size and development levels across the countries.

The dataset used in this study is an unbalanced panel due to data availability constraints across countries and years. The number of observations varies by country and variable, with a maximum total of 75 observations across the panel. At the country level, Kazakhstan, the Kyrgyz Republic, and Uzbekistan have differing sample sizes depending on data availability for each variable. Missing data are primarily due to incomplete reporting in the early years of the sample period. To ensure consistency and reliability of the estimation results, missing observations were handled using listwise deletion, and no imputation techniques were applied. This approach avoids introducing potential biases associated with artificial data generation while maintaining the integrity of the original dataset.

The correlation coefficients between the explanatory variables in the model are presented in table 3. A correlation coefficient of 1.000 represents a perfect positive correlation between two variables, and a coefficient of 0.000 represents the absence of a relationship. Correlation coefficients between 0.3 and 0.5 are considered weak, those between 0.5 and 0.7 represent a moderate relationship, and coefficients above 0.7 to

TABLE 3 Correlation Matrix

	lnco2	lngdp	lnfdi	lntrade	lnenergy
lnco2	1.0000				
lngdp	0.9365	1.0000			
lnfdi	0.7636	0.7691	1.0000		
lntrade	-0.3628	-0.5690	-0.1207	1.0000	
lnenergy	0.9853	0.9633	0.7789	-0.4320	1.0000

TABLE 4 Test Results of Variance Inflation Factor

Variable	VIF	1/VIF
ln _{gdp}	1.75	0.565032
ln _{fdi}	1.69	0.578466
ln _{trade}	1.18	0.865118
ln _{energy}	1.32	0.851125
Mean VIF	1.49	

1.000 represent strong relationships. The negative coefficients are interpreted in the same manner but represent negative relationships between variables (Frees 1995; Pesaran 2015).

The results of the variance inflation factor (VIF) test, which was used to determine the extent of multicollinearity among the independent variables, are presented in table 4. It can be noted that all the VIF values are less than 5. This suggests that multicollinearity is not a problem in the model. According to existing empirical standards, VIF values above 10 or tolerance values below 0.10 indicate multicollinearity problems.

In addition to the PMG estimator, alternative panel estimators such as the Mean Group (MG) and Dynamic Fixed Effects (DFE) approaches are reported in this study to ensure robustness of the results. The Hausman test confirms the appropriateness of the PMG estimator for the analysis. Furthermore, the existing literature suggests other estimation techniques, including the Common Correlated Effects Mean Group (CCEMG), system Generalized Method of Moments (GMM), and panel Dynamic Ordinary Least Squares (DOLS) or Fully Modified Ordinary Least Squares (FMOLS), which can address issues related to cross-sectional dependence, endogeneity, and cointegration. However, given the relatively small sample size and the focus on distinguishing between short-run and long-run dynamics, the PMG-ARDL framework is considered the most suitable approach for this study. The consistency of results across MG and DFE estimators further supports the robustness of the findings.

In general, the data and framework of methodology offer a consistent basis for analysis of the relationships between environmental and economic variables in the chosen Central Asian economies. The combination of high-quality data sources, well-defined variables, and appropriate econometric methodology ensures the validity of the empirical analysis and allows for correct interpretation of the results presented in the next section.

Results and Discussion

This section discusses and explains the empirical findings related to the relationship between carbon dioxide emissions and key economic variables in Kazakhstan, the Kyrgyz Republic, and Uzbekistan. The analysis begins with the use of panel unit root and cointegration tests to validate the appropriateness of the econometric model specification and to examine the existence of long-run equilibrium relationships among the variables. The results of the panel Autoregressive Distributed Lag model, using the Pooled Mean Group estimation technique, are then discussed to assess both the short- and long-run relationships. Finally, the panel Granger causality test is employed to examine the nature of causal relationships among the variables. In general, the findings provide significant evidence related to the role of economic growth, energy consumption, foreign direct investment, and trade openness in shaping environmental outcomes in the transition economies of Central Asia.

A potential concern in the analysis is reverse causality, particularly between economic growth and CO₂ emissions, as environmental degradation may also influence economic performance. The PMG-ARDL framework partially addresses this issue by incorporating lagged values of both dependent and independent variables, which helps to mitigate simultaneity bias and capture dynamic relationships. In addition, the error correction mechanism allows for distinguishing between short-run adjustments and long-run equilibrium relationships. However, the PMG approach does not fully eliminate endogeneity concerns, as contemporaneous feedback effects may still persist. To complement this, the study employs panel Granger causality tests, which provide further insights into the direction of relationships among variables. The results confirm the presence of causal linkages, supporting the robustness of the estimated relationships, although the findings should be interpreted with some caution.

The results of the stationarity test performed using various methods, including the Augmented Dickey-Fuller (ADF), and Phillips-Perron (PP) tests, are presented in table 5. Overall, most variables are non-stationary at level but become stationary after first differencing, indicating integration of order one, I(1). Specifically, CO₂ emissions (lnco2) and economic growth (lngdp) are non-stationary at level but stationary at first difference. Foreign direct investment (lnfdi) shows some evidence of stationarity at level in certain specifications, but is consistently stationary

TABLE 5 Unit Root Test Results (ADF and PP Tests)

	Level	Z(t)	ADF			PP			
			1st diff	Z(t)	Level	Z(t)	1st diff	Z(t)	
Inco2	Without time trend	-3.655	0.4492	-3.735	0.0015	-3.735	0.2501	-3.756	0.0016
	With time trend	-4.362	0.2264	-4.364	0.0126	-4.351	0.0605	-4.362	0.0126
Ingdp	Without time trend	-3.642	0.8767	-3.789	0.0275	-3.688	0.9485	-3.625	0.0000
	With time trend	-4.371	0.4182	-4.375	0.0129	-4.298	0.0451	-4.362	0.0000
Indfi	Without time trend	-3.754	0.2585	-3.691	0.0014	-3.811	0.2264	-3.589	0.0012
	With time trend	-4.380	0.3954	-4.452	0.0100	-4.422	0.0025	-4.362	0.0100
Intrade	Without time trend	-3.782	0.3955	-3.801	-2.995	-3.645	0.9658	-3.821	0.0362
	With time trend	-4.281	0.7097	-4.361	0.0281	-4.352	0.0005	-4.362	0.0459
Inenergy	Without time trend	-3.650	0.3951	-3.743	-2.877	-3.731	0.9544	-3.736	0.0352
	With time trend	-4.380	0.7158	-4.371	0.0250	-4.402	0.0005	-4.289	0.0452

after differencing. Similarly, trade openness (Intrade) and energy consumption (Inenergy) are non-stationary at level and become stationary at first difference.

The model’s robustness was also tested using the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares (CUSUMSQ) tests. As depicted in figure 1, the CUSUMSQ graph lies below the 5% significance level throughout the entire sample period ranging from 1997 to 2024. This implies that the model’s parameters are stable and that there are no structural breaks. Therefore, the short-run and long-run coefficients obtained from the panel ARDL approach are reliable and can be discussed in terms of their implications.

The results of the Pedroni panel cointegration test are summarized in table 6. Given that the majority of the *p*-values are less than 0.05, it is possible to reject the null hypothesis of no cointegration, and thus there is a long-run relationship between the variables. The existence of cointegration among the variables indicates that the variables share a common long-run behaviour, and the deviations from this behaviour in the short run are temporary. The findings above provide evidence that the panel ARDL approach can be used to capture both the short-run relationships and the long-run relationships between the variables.

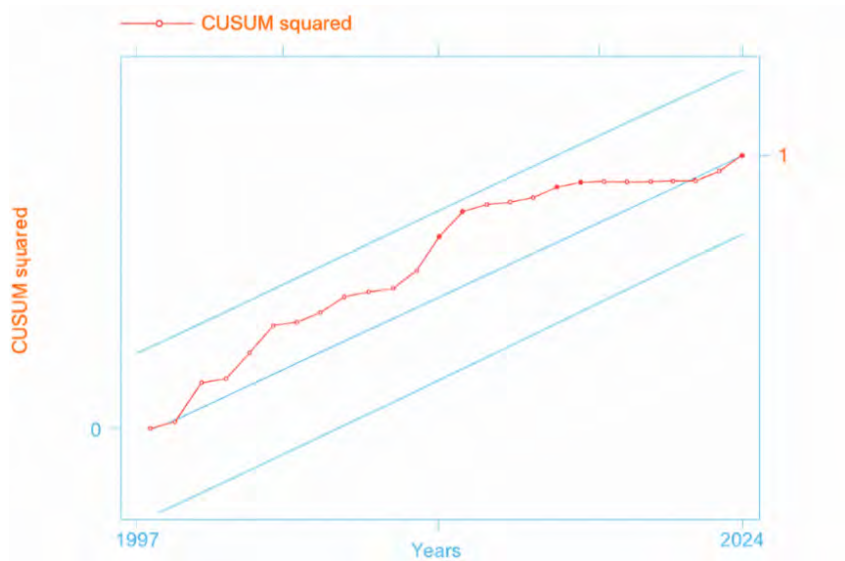


FIGURE 1 CUSUM and CUSUMSQ Plots for Model Stability

Figure 2 illustrates the dynamic multiplier effects derived from the PMG-ARDL model, showing the response of carbon dioxide emissions to changes in key explanatory variables over time. The results indicate that energy consumption has the strongest and most immediate positive impact on CO₂ emissions, with the effect gradually stabilizing as it approaches the long-run equilibrium. In contrast, economic growth exhibits a negative effect on emissions, which becomes more pronounced over time, supporting the environmental Kuznets Curve hypothesis. Trade openness and foreign direct investment show moderate and positive effects, with their impacts increasing gradually and converging smoothly in the long run. Overall, the adjustment paths confirm that the effects of

TABLE 6 Cointegration Pedroni Test

	Statistic	p-value
Within		
Modified variance ratio	0.4167	0.3377
Modified Phillips–Perron t	−0.6685	0.2526
Phillips–Perron t	−2.4576	0.0068
Augmented Dickey–Fuller t	−2.4185	0.0058
Between		
Modified Phillips–Perron t	−0.3454	0.3643
Phillips–Perron t	−2.5836	0.0051
Augmented Dickey–Fuller t	−2.2333	0.0136

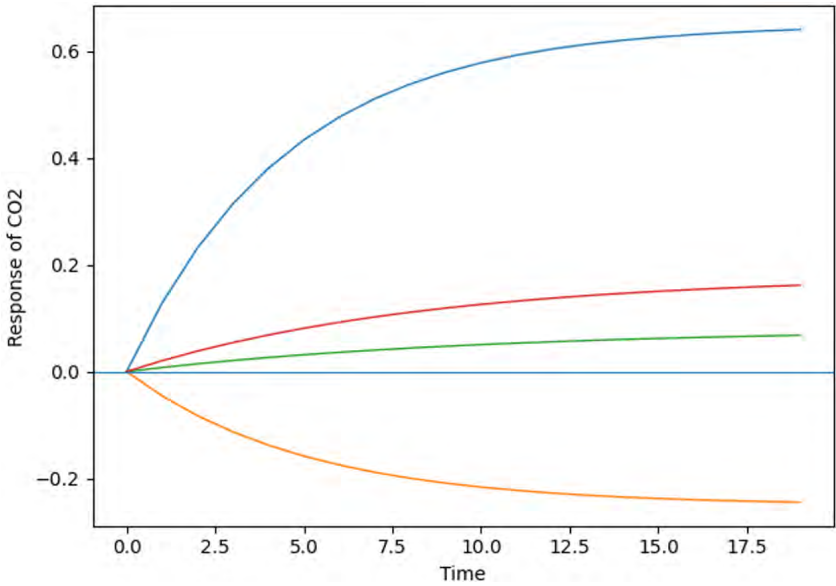


FIGURE 2 Dynamic Multipliers from the PMG-ARDL Model

the explanatory variables materialize progressively, highlighting the importance of long-run dynamics in explaining environmental outcomes in Central Asian economies.

Table 7 presents the results of the diagnostic tests. The findings indicate no evidence of serial correlation or heteroskedasticity, and the residuals are normally distributed. The Ramsey RESET test confirms correct model specification. In addition, the Pesaran’s test for cross-sectional dependence (CD) test suggests its absence, supporting the robustness and validity of the model.

Having confirmed the existence of stationarity and cointegration among the variables, the panel ARDL approach is employed to examine both long-run and short-run relationships between carbon dioxide

TABLE 7 Diagnostic Tests Summary

Test	Statistic	p-value	Result
Breusch–Godfrey Serial Correlation LM Test	1.34	0.27	No serial correlation
Breusch–Pagan Heteroskedasticity Test	0.91	0.34	No heteroskedasticity
Jarque–Bera Normality Test	1.88	0.39	Residuals normally distributed
Ramsey RESET Test	2.05	0.22	Model correctly specified

emissions, economic growth, foreign direct investment, trade openness, and energy use in the chosen Central Asian countries. The estimation results based on three alternative methods, namely the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators, are presented in table 8. To determine the best-performing model, a Hausman test was conducted to compare the three models. The obtained *p*-value of 0.660 fails to reject the null hypothesis, suggesting that the PMG estimator is the preferred model for interpretation. Moreover, the error correction term is negative and statistically significant, confirming the existence of a long-run relationship among the variables. The estimated coefficient (−0.432) indicates that approximately 43.2% of the deviation from the long-run equilibrium is corrected within one period, implying a relatively fast speed of adjustment.

TABLE 8 Panel ARDL Analysis

VARIABLES	PMG	MG	DFE
—ec	−0.432 (0.354)	−1.689** (0.734)	−0.711*** (0.155)
D.lngdp	−0.451 (0.499)	−0.626 (0.676)	−0.374 (0.342)
D.lnfdi	−0.0110* (0.0302)	−0.0329 (0.0406)	0.0123 (0.0141)
D.lntrade	−0.0470 (0.0667)	−0.323 (0.266)	−0.137** (0.0674)
D.lnenergy	0.307** (0.707)	−1.057 (0.736)	0.132 (0.208)
lngdp	−0.401*** (0.0690)	−0.284* (0.147)	−0.199*** (0.0706)
lnfdi	0.0790*** (0.0250)	0.0800** (0.0334)	0.00463 (0.0218)
lntrade	0.181*** (0.0555)	0.0133 (0.0854)	0.255*** (0.0636)
lnenergy	1.194*** (0.0718)	0.967*** (0.137)	1.226*** (0.0878)
Constant	3.755 (2.912)	6.375** (2.809)	3.183** (1.400)
Observations	53	53	53
	PMG OR MG	DFE OR MG	DFE OR PMG
Hausman chi2	40.25	22.58	23.18
Prob>chi2	0.650	0.0003	0.0001

NOTES Standard errors are shown in parentheses. The symbols ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The long-run results based on the PMG estimator indicate that GDP, foreign direct investment, trade openness, and energy consumption have all made statistically significant contributions to carbon dioxide emissions at the 1% significance level, while none of the variables have made any significant contributions in the short run. It is pertinent to note that economic growth has a negative and statistically significant long-run relationship with emissions, indicating that a 1% increase in GDP is associated with an estimated 0.401% decrease in CO₂ emissions. This finding suggests that economic growth in the studied Central Asian countries may eventually result in environmental improvement. This is because higher levels of income may facilitate the development of cleaner technologies, improvements in energy efficiency, and more stringent environmental policies, ultimately resulting in a reduction in emissions over time. This finding provides partial support to the environmental Kuznets Curve hypothesis, which suggests that environmental degradation gradually decreases beyond a certain level of economic development.

On the other hand, foreign direct investment has a positive and significant effect on carbon dioxide emissions. In particular, a 1% increase in FDI is associated with a 0.0790% increase in CO₂ emissions, suggesting that the inflow of FDI in the selected Central Asian economies contributes to the deterioration of the environment. This result suggests that the inflow of foreign investment in the selected Central Asian economies is primarily focused on energy and pollution-intensive industries. The result confirms the pollution haven hypothesis, which states that foreign investors are attracted to countries that have less stringent environmental policies. From a policy point of view, this suggests that governments should focus on establishing more stringent environmental policies.

In addition, a 1% increase in trade openness is associated with a 0.181% increase in CO₂ emissions in the long run, but there is no significant short-run relationship. This finding indicates that the rise in trade openness has been accompanied by higher production activities, energy use, and transportation, which are major factors in environmental degradation. While trade can be a catalyst for technology transfer and improvement in efficiency, it is apparent that the nature of trade in Central Asian countries is driven by energy-intensive and resource-based exports. It is recommended that policymakers adopt more environmentally friendly trade policies and encourage the use of cleaner production technology to offset the negative effects of trade expansion.

Energy consumption also has a strong and positive long-run effect on CO₂ emissions. The results indicate that with every 1% increase in energy consumption, there is a 1.194% increase in CO₂ emissions. This result confirms that energy consumption is still the main cause of environmental degradation in the chosen countries. The overdependence on fossil fuels and energy-intensive production systems are major factors that contribute to the increase in emissions. This highlights the need to shift to renewable energy sources and adopt low-carbon technologies to ensure sustainable development.

The short-run results indicate a lack of statistical significance for most variables, implying that the relationship between economic growth, foreign direct investment, and trade openness, and CO₂ emissions is a long-run process. However, energy consumption has a positive short-run relationship with CO₂ emissions, implying that energy consumption has an immediate effect on environmental quality.

The estimated long-run coefficients can be interpreted as elasticities. Specifically, a 1% increase in energy consumption leads to a 1.194% increase in CO₂ emissions, confirming that energy use is the dominant driver of environmental degradation in the region. In practical terms, this implies that even small increases in energy consumption can result in disproportionately higher emissions, given the heavy reliance on fossil fuels in Central Asian economies. In contrast, a 1% increase in economic growth reduces CO₂ emissions by approximately 0.401%, suggesting that higher income levels may promote cleaner technologies and improved energy efficiency. Trade openness and foreign direct investment also have positive effects, where a 1% increase in trade and FDI leads to increases of 0.181% and 0.079%, respectively, in CO₂ emissions. These findings imply that without appropriate environmental regulations, economic integration and investment inflows may contribute to environmental degradation.

To investigate the causal relationships among the variables, the panel Granger non-causality test was performed using the Juodis et al. (2021) method. The results presented in table 9 show that economic growth, foreign direct investment, trade openness, and energy consumption Granger-cause carbon dioxide emissions. In the first step, we test the null hypothesis of no Granger causality between economic growth and energy consumption. The *p*-values of the Juodis et al. (2021) Granger non-causality test reveal that all variables Granger-cause CO₂ emissions in Kazakhstan, the Kyrgyz Republic, and Uzbekistan. The findings emphasize

TABLE 9 Granger Non-Causality Test Results Applying Juodis et al. (2021) Approach

Null Hypothesis	Statistics
CO ₂ emissions are not Granger-caused by economic growth.	104.63166***
CO ₂ emissions are not Granger-caused by foreign direct investment.	21.255775***
CO ₂ emissions are not Granger-caused by trade openness	5538.0595***
CO ₂ emissions are not Granger-caused by energy consumption	166.07241***

NOTE ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

that economic growth, foreign direct investment, trade openness, and energy consumption have played a significant role in determining environmental outcomes in the region. Specifically, the findings of strong causality from energy consumption to environmental emissions support the argument that energy consumption is the key driver of environmental degradation in Central Asian economies. Additionally, the presence of significant causal links between foreign direct investment and trade openness and environmental emissions indicates that economic globalization and industrialization are important factors in increasing environmental emissions.

The empirical results of this study have a number of significant implications for policymakers to ensure sustainable economic growth and environmental protection in Central Asian economies. The positive relationship between energy consumption and carbon dioxide emissions confirms that energy consumption is still the main cause of environmental degradation in the region. Therefore, policymakers should focus on the development of cleaner and renewable energy resources like solar, wind, and hydropower energy. Energy efficiency in industrial, transportation, and power sectors should also be improved to reduce emissions without hampering economic growth. Policymakers should therefore encourage investment in energy-efficient technologies and develop a favourable policy environment to promote low-carbon growth.

Moreover, policy implications differ across the selected Central Asian countries due to variations in economic structure and energy dependence. In Kazakhstan, where emissions and energy use are relatively high, priority should be given to energy subsidy reform and the promotion of renewable energy investments to reduce reliance on fossil fuels. In the Kyrgyz Republic, which has a smaller economic scale and lower emissions, policies should focus on improving energy efficiency and supporting sustainable infrastructure development. In Uzbekistan, where industrialization and foreign investment are expanding, stricter envi-

ronmental screening of FDI projects and the adoption of cleaner technologies are essential. In addition, region-wide policy instruments such as green trade incentives, carbon pricing mechanisms, and support for clean energy technologies can help mitigate the environmental impact of trade openness and economic growth. Strengthening environmental regulations and promoting technology transfer will be crucial for achieving sustainable development across Central Asia.

The findings highlight important trade-offs between economic growth and environmental sustainability in Central Asian economies. While economic growth contributes to reducing emissions in the long run, energy consumption, trade openness, and foreign direct investment increase environmental pressure. This suggests that pursuing rapid growth without environmental safeguards may lead to higher emissions in the short to medium term. To balance these objectives, policymakers should adopt measurable targets such as reducing carbon intensity (CO₂ emissions per unit of GDP) by a specific percentage, increasing the share of renewable energy in total energy consumption, and improving energy efficiency in key sectors. In addition, setting clear environmental standards for foreign investment and introducing green trade incentives can help align economic expansion with sustainability goals. These policy targets can support a transition toward low-carbon growth while maintaining economic development momentum.

The empirical results also confirm that foreign direct investment and trade openness are factors that increase carbon emissions in the long run. Policymakers should adopt more stringent environmental protection policies for foreign investment projects and offer incentives for environmentally responsible and technology-driven investments. The promotion of green foreign direct investment, innovation, and clean production practices can mitigate the negative effects of economic globalization on the environment. Furthermore, trade policies should encourage the export of environmentally sustainable products and facilitate the transfer of clean technology. Finally, the negative long-term relationship between economic growth and carbon emissions indicates that sustainable economic development can lead to environmental improvement. Policymakers should incorporate environmental factors into their country's development plans and enhance regional cooperation on energy and environmental issues. A unified policy approach that focuses on renewable energy, green infrastructure, and sustainable industrialization can enable Central Asian na-

tions to achieve economic growth in the long term while mitigating environmental degradation.

Conclusion

This paper investigates the relationship between carbon emissions, economic growth, energy use, foreign direct investment, and trade openness in Kazakhstan, the Kyrgyz Republic, and Uzbekistan from 1997 to 2024. The Pooled Mean Group estimator in the panel Autoregressive Distributed Lag model was used to analyse the relationship between carbon emissions and their economic determinants. The results show that there is a long-run relationship between carbon emissions and their economic determinants. The results also show that energy use, foreign direct investment, and trade openness are factors that increase carbon emissions in the long run, but economic growth reduces carbon emissions. Energy use is the dominant factor that affects environmental degradation in the short run. Moreover, the results of the panel Granger causality test indicate that economic growth, foreign direct investment, trade openness, and energy consumption are all significant predictors of carbon dioxide emissions for the chosen Central Asian economies.

The study has made several contributions to the existing body of knowledge. Firstly, it has offered new empirical evidence on the energy–growth–environment nexus in Central Asia, a region that has been relatively underrepresented in the existing literature. Secondly, it has considered foreign direct investment and trade openness, providing a more complete picture of the factors that influence carbon emissions in transition economies. Thirdly, it has used a panel Autoregressive Distributed Lag model with the Pooled Mean Group estimator to capture both short-term and long-term relationships between countries with similar structural characteristics. The results of the study have helped to provide a better understanding of the role of economic development, globalization, and energy use in shaping environmental sustainability in resource-dependent economies.

Despite the contributions, the study has a number of limitations. Firstly, it has considered only three Central Asian economies because of data availability constraints, which may affect the generalizability of the results to other regions. Secondly, it has used aggregate measures of energy consumption and foreign direct investment without making a distinction between renewable and non-renewable energy sources and between different types of investment. Future studies may consider expanding the

sample to include other countries and use other variables such as the consumption of renewable energy resources, innovation, and environmental policy indicators to give a more nuanced analysis of environmental sustainability. Future studies may also use other econometric models to capture the complex relationships between economic activities and environmental outcomes.

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