“Trade openness, economic growth, and carbon emissions in Uzbekistan: Evidence from ARDL and WTO accession context”

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TRADE OPENNESS, ECONOMIC GROWTH, AND CARBON EMISSIONS IN UZBEKISTAN: EVIDENCE FROM ARDL AND WTO ACCESSION CONTEXT

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Abstract

The environmental consequences of trade liberalization remain a critical concern for developing countries pursuing World Trade Organization (WTO) membership. Uzbekistan's recent economic reforms and accelerated integration into global markets necessitate an empirical assessment of how trade openness and economic growth interact with carbon emissions. This study aims to examine the long-run and short-run relationships between real GDP, trade openness, and per capita CO_2 emissions in Uzbekistan. The Autoregressive Distributed Lag (ARDL) bounds testing approach is applied to annual time series data from 1997 to 2024. The Augmented Dickey–Fuller test confirms that all variables are integrated of order I(1), and the ARDL(1,4,0) model is selected based on the Akaike Information Criterion. The bounds test F-statistic (4.607) exceeds the upper critical value at the 5% significance level, confirming long-run cointegration. The estimated long-run elasticities suggest that a 1% increase in GDP is associated with a 0.196% decrease in CO_2 emissions while a 1% increase in trade openness corresponds to a 0.185% reduction in emissions. These findings support the pollution halo hypothesis. The error correction coefficient of –0.94 indicates a rapid adjustment toward equilibrium. Validated by robust diagnostic tests, the results provide empirical evidence that Uzbekistan's trade integration is compatible with environmental sustainability, offering policy guidance for aligning WTO accession strategies with green development objectives.

Keywords environmental sustainability, cointegration, carbon intensity, technological modernization, green trade policy, transition economy, sustainable development

JEL Classification C32, F18, Q53, Q56, O44

INTRODUCTION

Trade liberalization and deeper integration into the world economy are widely viewed as engines of productivity growth and structural transformation. However, the environmental consequences of expanding trade and output remain debated, particularly for developing and transition economies where growth often relies on energy-intensive production and carbon-intensive power systems. The empirical literature suggests that the trade–environment nexus is not unidirectional: trade can increase emissions through scale effects, but it can also reduce emissions by enabling technology transfer, upgrading production processes, and strengthening environmental standards through international market pressures. This ambiguity is commonly discussed through the pollution haven and pollution halo hypotheses, alongside broader development perspectives such as the Environmental Kuznets Curve (EKC) framework (Grossman & Krueger, 1995; Antweiler et al., 2001; Copeland & Taylor, 2004).

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Uzbekistan provides a timely and policy-relevant context for examining these mechanisms. Over the past decade, the country has implemented broad market reforms to accelerate economic growth, attract investment, and expand external trade. At the same time, the process of accession negotiations with the World Trade Organization (WTO) increases the importance of aligning domestic economic modernization with evolving international requirements, including technical regulations, product standards, and environmental governance expectations embedded in global value chains. In this setting, the key policy concern is whether increasing trade integration and rising income are associated with higher carbon emissions, or whether they coincide with cleaner production patterns and declining carbon intensity.

Despite growing international evidence on the relationships between trade openness, growth, and emissions, country-specific results remain mixed and highly dependent on economic structure, energy composition, institutional quality, and stage of development. For Uzbekistan, the empirical literature is still relatively limited and often focuses on energy consumption or aggregate growth–emissions links without explicitly accounting for trade integration and the WTO-related reform context. Moreover, many studies rely on methods that do not fully exploit the distinction between short-run adjustment dynamics and long-run equilibrium relationships. This creates an applied research gap: policymakers need evidence that separates temporary emission responses from structural, long-run effects that matter for designing sustainable trade and industrial strategies.

This study addresses this gap by empirically investigating the relationship between per capita CO_2 emissions, real GDP, and trade openness in Uzbekistan using the autoregressive distributed lag (ARDL) bounds testing approach on annual data for 1997–2024. The ARDL framework is particularly suitable for small samples and for variables integrated of mixed orders I(0) / I(1), while enabling simultaneous estimation of long-run elasticities and short-run dynamics through an error correction mechanism. The study contributes to the literature in three ways. First, it provides updated time-series evidence for Uzbekistan during a period of intensified trade reforms and WTO accession efforts. Second, it explicitly evaluates whether the observed trade–emissions relationship aligns more closely with the pollution haven or pollution halo hypothesis. Third, it quantifies both long-run and short-run responses, offering policy-relevant insight into how quickly deviations from long-run equilibrium are corrected.

1. LITERATURE REVIEW

The relationship between macroeconomic factors and environmental indicators is one of the important directions of ecological economics and international trade theories. The relationship between CO_2 emissions and economic growth is usually analyzed within the framework of the Environmental Kuznets Curve (EKC). Grossman and Krueger (1995), Selden and Song (1994), and Shafik and Bandyopadhyay (1992) are considered to be the founders of the idea of EKC. According to their results, economic growth initially leads to an increase in emissions (scale effect), and then to a decrease through technological modernization (technique effect). In recent years, the results of EKC have been partially confirmed in developing countries, and the level of economic modernization, energy composition, and trade policy are noted as key factors in shaping this process.

There are two main hypotheses in the scientific literature on the relationship between trade openness and emissions: the pollution haven and the pollution halo. According to the pollution haven hypothesis, trade openness can lead to the relocation of polluting production to countries with less environmental requirements. This phenomenon, often referred to as carbon leakage, illustrates the difficulties in managing environmental impacts in a globalized economy, as firms try to minimize the costs associated with reducing emissions by moving to pollution havens. Conversely, the pollution halo hypothesis suggests that trade openness can facilitate the introduction of cleaner technologies and production methods, potentially leading to reduced emissions. This perspective highlights the positive environmental outcomes that can result from increased trade, especially when countries leverage their comparative advantages in cleaner production processes.

The effectiveness of these hypotheses is significantly affected by the stringency of environmental regulations in different countries. Stricter regulations in one region can inadvertently increase emissions elsewhere when firms move to regions with more lenient standards. This dynamic further substantiates the importance of international environmental agreements that help reduce the risks of carbon leakage and promote sustainable trade practices. Ultimately, the interaction between trade openness and emissions is complex, requiring a clear and thorough understanding of the pollution haven and pollution halo hypotheses. Policymakers will need to take these dynamics into account when designing climate change mitigation and sustainable development strategies, ensuring that trade policies are consistent with environmental objectives. Copeland and Taylor (2004) and Antweiler et al. (2001) have provided theoretical support for this mechanism.

Trade openness can lead to the diffusion of clean technologies by facilitating access to advanced technologies and practices from developed countries. This is particularly evident in the case of China, where higher trade openness is associated with lower CO_2 emissions intensity in low-carbon sectors, suggesting that trade can help promote the adoption of clean technologies (Fan et al., 2019).

The adoption of clean technologies is also influenced by international competition, which can increase per-unit emission taxes and reduce production subsidies, thereby encouraging firms to adopt clean technologies earlier than in authoritarian times (Jebli & Youssef, 2013).

In the context of the EU-18 countries, trade openness has been shown to increase CO_2 emissions, but it also supports the pollution halo hypothesis, which suggests that trade can have both positive and negative environmental outcomes, depending on the context (Tachie et al., 2020).

Elmarzougui et al. (2013) support the pollution halo hypothesis for CO_2 emissions in Africa, suggesting that trade openness can lead to environmental improvements in some regions.

There is a very extensive and in-depth study in the scientific literature on the impact of energy consumption, industrial composition, and technological modernization on CO_2 emissions, and this area is one of the most actively developing sectors of ecological economics (Halmuratov et al., 2025b). The relevance of this issue is that energy consumption plays a central role in the overall structure of economic growth, the industrial composition determines the production structure of a country, and technological progress shapes the environmental outcomes of these processes. Therefore, the energy–industry–technology triad has been deeply analyzed in many theoretical and empirical studies as the main driving force of carbon emissions dynamics.

Stern (2004) argues that energy efficiency and technological progress play a fundamental role in the dynamics of emissions. He claims that economic growth not only increases energy consumption but also creates opportunities to reduce CO_2 emissions per unit of energy through technological modernization. Stern's (2004) structural decomposition approach shows that emissions depend on the interaction of factors such as production volume, energy intensity, and carbon intensity. This approach emphasizes the need to interpret the impact of energy consumption on CO_2 emissions not as independent of each other, but as a complex systemic process.

Furthermore, the causal relationship between energy consumption and emissions is often closely linked to a country's industrial structure. In economies with a high share of heavy industry, energy consumption is often based on carbon-intensive sources, which increases emissions. On the other hand, the expansion of the light industry and the service sector can reduce pollution through technological modernization of production processes and increased energy efficiency. Changes in the structure of production, therefore, have a direct and indirect impact on CO_2 emissions.

P. Narayan and S. Narayan (2010) analyzed the relationship between energy consumption, economic growth, and CO_2 emissions using an ARDL model and found that energy consumption is the main driver of CO_2 emissions in developing countries. They also showed that the composition of the energy market (oil, gas, and coal share) and the level of technological modernization can signifi-

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cantly change the level of emissions. The empirical results show that the short- and long-term effects of energy consumption are not the same, with energy consumption increasing emissions in the short term, while in the long term this effect can be reduced or even reversed as a result of technological changes (P. Narayan & S. Narayan, 2010).

Shahbaz and Lean (2012) also used the ARDL approach to capture the complex dynamics between energy consumption, economic activity, and emissions. Their results suggest that economic expansion initially increases CO_2 emissions, but that over time, as economic structure changes and energy efficiency increases, pollution can decrease. This suggests that the technological stage part of the Environmental Kuznets Curve (EKC) hypothesis – that is, the share of clean technologies increases as the economy develops – is being confirmed in practice (Shahbaz & Lean, 2012).

In recent years, technological modernization and the introduction of clean energy sources have also been seen as key factors changing the global emissions dynamics. While energy efficiency gains in developed countries have helped reduce emissions, rising energy demand in developing countries has increased emissions. Therefore, technological diffusion, investments in energy markets, and the import of clean technologies through foreign trade are recognized in many studies as factors leading to long-term reductions in CO_2 emissions.

The link between trade policy and environmental standards is of strategic importance in the process of countries' accession to the WTO. The new global trading system requires not only the reduction of tariff and non-tariff barriers, but also environmental governance mechanisms compatible with international markets. The WTO report notes that WTO members are moving to a comprehensive framework that includes technical regulations, environmental certification standards, product safety requirements, green production standards, and cross-border monitoring systems to strengthen environmental responsibility in the process of trade liberalization. This approach is aimed at ensuring that trade growth is not limited to increasing economic efficiency but also contributes to environmental sustainability.

The expansion of environmental standards in the international arena shows that WTO member states are accelerating technological modernization at the same time as increasing environmental requirements in trade processes. For example, environmental certificates for export-oriented products have become a market requirement. Such standards force industrial enterprises to introduce clean technologies, reduce waste, increase energy efficiency, and control carbon emissions. Thus, environmental standards, integrated into WTO trade policy, are becoming not only an obligation for countries but also a powerful catalyst for technological transformation.

This issue is particularly relevant in the context of Uzbekistan. As the country accelerates its WTO accession process, aligning trade policy with international environmental requirements is a complex but necessary task, given the high carbon intensity of the existing industrial structure. In Uzbekistan, the introduction of environmental regulations, technical standards, and an environmental monitoring infrastructure in line with WTO requirements is becoming a priority area of state policy. This process requires a review of the energy base of the economy, resource consumption, and production technologies.

However, the existing literature on environmental-economic relationships in Uzbekistan is still limited. The analysis conducted by IEA (2020) focuses more on energy sector reforms and energy efficiency programs, and does not delve into the environmental consequences of global trade integration. ADB (2019) analyzed the early stages of economic liberalization, the reduction of trade barriers, and indicators of overall macroeconomic growth. However, the empirical relationship between trade openness, technological diffusion, and CO_2 emissions has not yet been sufficiently explored, especially in the context of increasing environmental standards in the process of WTO accession.

The empirical gap surrounding the relationship between environmental requirements, technology imports, international environmental standards, and trade openness presents a significant opportunity for research, particularly in the context of Uzbekistan. Understanding changes in environmental requirements is crucial as the country navigates the complexities of World Trade Organization (WTO) accession. These requirements can influence domestic production and environmental policies, necessitating a detailed study of their impact on CO_2 emissions and economic growth. Trade openness, which refers to a country's participation in international trade, has been shown to have both positive and negative environmental consequences. The literature suggests that while trade can stimulate economic growth, it can also lead to increased CO_2 emissions, especially if it is not governed by strict environmental standards (Shahbaz et al., 2014).

Therefore, it is important to assess the dynamics of technology imports, as importing clean technologies can reduce the negative environmental impacts associated with trade. High-precision econometric methods, such as autoregressive distributed lag (ARDL) and error correction models (ECM), are essential to effectively analyze these relationships. These methods allow researchers to examine the short-run and long-run relationships between CO_2 emissions, economic growth, and trade openness, providing a solid basis for policy recommendations (Heil & Selden, 2001). Overall, addressing these interrelated issues not only fills an important scientific gap, but also provides policymakers in Uzbekistan with the necessary insights to formulate strategies that promote sustainable economic growth while adhering to international environmental standards.

The aim of this study is to empirically determine whether Uzbekistan's increasing integration into global markets contributes to environmental degradation or improvement by quantifying the long-run and short-run elasticities between macroeconomic indicators and carbon emissions.

2. METHODS

To examine the relationship between economic growth, trade openness, and environmental quality in Uzbekistan, this study adopts a functional framework in which carbon emissions depend on income level and trade integration. The environmental impact function can be expressed as:

$$CO_{2t} = f\left(GDP_t, TO_t\right), \tag{1}$$

where CO_{2t} represents per capita carbon dioxide emissions; GDP_t denotes real gross domestic product per capita, and TO_t indicates trade openness measured as the ratio of total trade to GDP.

To reduce heteroscedasticity and interpret the estimated coefficients as elasticities, all variables are transformed into natural logarithms. The log-linear model is specified as:

$$\ln CO_{2t} = \alpha_0 + \alpha_1 \ln GDP_t + \alpha_2 \ln TO_t + u_t, \tag{2}$$

where α_0 is the intercept term, α_1 and α_2 represent long-run elasticities of carbon emissions with respect to income and trade openness, respectively, and u_t is the stochastic error term.

Before estimating the dynamic relationship, the stationarity properties of the variables are tested using the Augmented Dickey–Fuller (ADF) unit root test (Halmuratov et al., 2025a). The general ADF regression equation is:

$$\Delta Y_t = \mu + \delta t + \rho Y_{t-1} + \sum_{i=1}^{k} \phi_i \Delta Y_{t-i} + \varepsilon_t, \tag{3}$$

where Δ denotes the first difference operator, Y_t represents the variable under investigation, t is a time trend, k is the optimal lag length, and ε_t is a white-noise error term.

Given that the variables may exhibit a mixture of integration orders I(0) and I(1), the autoregressive distributed lag (ARDL) approach developed by Pesaran et al. (2001) is employed. The ARDL model allows simultaneous estimation of short-run dynamics and long-run equilibrium relationships within a single equation framework (Xolmurotov et al., 2025). The unrestricted ARDL(p,q,r) model can be written as:

$$\ln CO_{2t} = \beta_0 + \sum_{i=1}^{p} \beta_i \ln CO_{2,t-i} + \sum_{j=0}^{q} \gamma_j \ln GDP_{t-j} + \sum_{k=0}^{r} \theta_k \ln TO_{t-k} + \varepsilon_t, \tag{4}$$

where β_i are autoregressive coefficients, γ_j and θ_k represent distributed lag coefficients of GDP and trade openness, respectively, and ε_t is the error term.

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To test for the existence of a long-run relationship among the variables, the ARDL bounds testing procedure is applied through the conditional error correction representation:

$$\Delta \ln CO_{2t} = \lambda_0 + \lambda_1 \ln CO_{2,t-1} + \lambda_2 \ln GDP_{t-1} + \lambda_3 \ln TO_{t-1} + \sum_{i=1}^{p-1} \psi_i \Delta \ln CO_{2,t-i} + \sum_{j=0}^{q-1} \omega_j \Delta \ln GDP_{t-j} + \sum_{k=0}^{r-1} \varphi_k \Delta \ln TO_{t-k} + \varepsilon_t, \quad (5)$$

where λ_1, λ_2, and λ_3 denote long-run parameters, while ψ_1, ω_j, and φ_k capture short-run dynamic adjustments. The null hypothesis of no cointegration is tested using an *F*-statistic comparing the joint significance of lagged level variables (Yulduz et al., 2025; F. Xolmurotov & X. Xolmuratov, 2025).

The long-run elasticities of GDP and trade openness with respect to carbon emissions are derived from the estimated ARDL coefficients as follows:

$$LR_{GDP} = -\frac{\sum_{j=0}^{q} \gamma_j}{1 - \sum_{i=1}^{p} \beta_i}, \quad (6)$$

$$LR_{TO} = -\frac{\sum_{k=0}^{r} \theta_k}{1 - \sum_{i=1}^{p} \beta_i}, \quad (7)$$

where LR_{GDP} and LR_{TO} denote long-run elasticities of carbon emissions with respect to GDP and trade openness, respectively.

Once cointegration is confirmed, the short-run dynamics are estimated using the error correction model (ECM):

$$\Delta \ln CO_{2t} = \eta_0 + \sum_{i=1}^{p-1} \eta_i \Delta \ln CO_{2,t-i} + \sum_{j=0}^{q-1} \kappa_j \Delta \ln GDP_{t-j} + \sum_{k=0}^{r-1} \xi_k \Delta \ln TO_{t-k} + \psi \cdot ECM_{t-1} + \varepsilon_t, \quad (8)$$

where ECM_{t-1} is the lagged error correction term defined as:

$$ECM_{t-1} = \ln CO_{2,t-1} - \hat{\alpha}_0 - \hat{\alpha}_1 \ln GDP_{t-1} - \hat{\alpha}_2 \ln TO_{t-1}, \quad (9)$$

and ψ represents the speed of adjustment toward the long-run equilibrium. A negative and statistically significant coefficient confirms the existence of cointegration and indicates how quickly short-run deviations converge to equilibrium.

2.1. Data and estimation procedure

The empirical analysis is conducted using annual time-series data for Uzbekistan covering the period 1997–2024. Carbon dioxide emissions per capita are measured in metric tons, real GDP per capita is expressed in constant U.S. dollars, and trade openness is calculated as the ratio of total exports and imports to GDP. The data are obtained from internationally recognized sources, including the World Bank and related statistical databases.

The optimal lag structure of the ARDL model is selected using the Akaike Information Criterion (AIC). After estimating the model, several diagnostic tests are performed to ensure robustness, including the Breusch–Godfrey serial correlation test, Breusch–Pagan–Godfrey heteroscedasticity test, Ramsey RESET specification test, Jarque–Bera normality test, and stability tests based on the cumulative sum (CUSUM) procedure. These tests confirm the adequacy, stability, and reliability of the estimated model.

3. RESULTS

Descriptive statistics (Table 1), as an initial step in the analysis, allow us to identify the general characteristics of the variables used in the study and provide basic information about their distribution, central tendency, and dispersion. This step helps to get an initial idea of how indicators such as CO_2 emissions, economic growth, and foreign trade openness fluctuate over time, whether the distribution is symmetric or skewed, and whether it is close to normal. Knowledge of such statistical properties is important for ensuring model stability and reliable interpretation of the relationships between variables when using the ARDL approach.

The results of the analysis were based on 28 years and were presented in logarithmic form for three main variables: LNCO2, LNGDP, and LNTO. The mean value of LNCO2 of 1.495 and the standard

Table 1. Descriptive statistics of log-transformed variables

Variables	LNCO2	LNGDP	LNTO
Mean	1.495133	24.31789	–0.617223
Median	1.537352	24.71311	–0.556370
Maximum	1.678778	25.46790	–0.226299
Minimum	1.249331	22.99413	–1.231265
Std. Dev.	0.135318	0.845765	0.273780
Skewness	–0.421775	–0.268785	–0.652409
Kurtosis	1.719856	1.431185	2.517770
Jarque–Bera	2.742069	3.208523	2.257610
Probability	0.253844	0.201038	0.323420
Sum	41.86373	680.9009	–17.28224
Sum Sq. Dev.	0.494399	19.31361	2.023803
Observations	28	28	28

deviation of 0.135 indicate that emissions have been changing relatively steadily. Although its distribution is slightly skewed to the left, the low kurtosis indicates that the distribution is flat, and the Jarque–Bera test does not reject the hypothesis of a normal distribution.

The LNGDP variable has the largest average value, which is explained by the scale of the macroeconomic indicator. The low standard deviation indicates a consistent course of economic growth. The closeness of the skewness and kurtosis values and the non-significance of the Jarque–Bera test confirm that the LNGDP series has favorable properties for regression.

The negative mean of the LNTO is due to the logarithmic transformation of the foreign trade openness index, and its variance indicates that the fluctuations are inherent in economic processes. In comparison, it has the most skewed distribution, but the closeness of the kurtosis to normal and the non-significant result of the Jarque–Bera test indicate that the LNTO variable is also stable enough for regression.

In general, all three variables are free of extreme jumps, have a near-normal distribution, and exhibit stable fluctuations over time. Such features provide a solid empirical basis for reliable estimation of the ARDL model, stability of parameters, and accurate formulation of economic interpretations of elasticities.

Determining stationarity in time series data is one of the most critical stages of analysis, since non-stationary series can reflect the regression results in the form of spurious correlations and, as a result, lead to incorrect economic conclusions. The ARDL method is characterized by the fact that it flexibly allows variables to be I(0) or I(1), but the series are completely unsuitable for the model if they are integrated in the I(2) order. Therefore, the widely used Augmented Dickey–Fuller (ADF) test (Table 2) was used to determine the integration order of all variables and assess the stability properties of the data over time. The null hypothesis of the test indicates that the series has a primary root, that is, not stationary; in cases where the null hypothesis is rejected, the series is considered stationary. The results obtained confirmed that all variables are in the order of I(0) or I(1), which confirms that the necessary condition for applying the ARDL model is met and increases the likelihood of the existence of long-run cointegration between the variables (Nurjanov et al., 2025).

To determine the presence of a long-run relationship, the bounds test developed by Pesaran et al. (2001) was used within the ARDL approach (Table 3). This test tests the null hypothesis that the long-run parameters in the regression equation are jointly statistically insignificant. According to the hypothesis, if $\lambda 1 = \lambda 2 = \lambda 3 = 0$, then there is no cointegration between the variables. In cases where the value of the F-statistic is greater than the critical value of I(1), which is the upper limit, the null hypothesis is rejected and a conclusion is drawn that there is a long-run relationship. If the value is less than the lower limit (I(0)), the absence of cointegration is confirmed. In cases where the F-statistic is in the range, the result is ambiguous, and additional tests or alternative methods are required. These results make the estimation of long-run and short-run coefficients within the ARDL model scientifically justified and allow us to con-

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Table 2. Augmented Dickey–Fuller unit root test results

Variable	Level ADF statistics	Level p-qvalue	Result (Level)	1st Diff ADF statistics	1st Diff p-value	Results (1st Diff)	Integrate
LNCO2	–0.859	0.3345	non-stationary	–6.345	0.0000	stationary	I(1)
LNGDP	+1.224	0.9392	non-stationary	–2.233	0.0272	stationary	I(1)
LNTO	–1.075	0.2473	non-stationary	–4.675	0.0000	stationary	I(1)

Table 3. ARDL bounds test results for cointegration

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
			Asymptotic	N = 1000
F-statistic	4.607143	10%	2.63	3.35
		5%	3.1	3.87
k	2	2.5%	3.55	4.38
		1%	4.13	5

tinue the next stages of the study in a fully justified manner.

The results of the bounds test used in this study were crucial in determining the presence of a long-run relationship. The calculated F-statistic value is 4.607, and the critical limits at the 5% confidence level for the two compared regressors in the model are determined as I(0) = 3.10 and I(1) = 3.87. Since the result obtained is greater than the upper limit value, the condition F-statistic > I(1) is fully met. This leads to the rejection of the null hypothesis and the scientific conclusion that there is long-run cointegration between the variables (Pesaran et al., 2004). Thus, a stable, statistically reliable equilibrium relationship between CO_2 emissions, economic growth, and foreign trade openness is formed, which confirms that the main condition necessary for estimating long-run elasticities in the ARDL approach is fully met (Xolmurotov et al., 2025).

The result of the bounds test (Table 4) reinforces the main assumption of the study: economic growth and foreign trade openness have a long-term structural relationship with CO_2 emissions in the conditions of Uzbekistan. This interaction implies the existence of a continuous and deep mechanism between the country's economic system, trade integration, and environmental indicators. The confirmation of long-term equilibrium allows us to further interpret the impact of economic growth and trade openness on CO_2 emissions using the ARDL model with long-term parameters, as well as to estimate the error correction mechanism (ECM).

Correctly specifying the lag structure in an ARDL model is crucial for the robustness and economic significance of the estimation results to be reliably reflected (Kadirova et al., 2025). In particular, since environmental indicators such as CO_2 emissions are inert systems that respond to economic processes not immediately, but over time, the selection of optimal lags makes it possible to determine the true lagged effects of environmental and macroeconomic dynamics. In cases where the lag length is incorrectly set, autocorrelation, incorrectly estimated parameters, or distortion of economic interpretation may be observed in the model.

The Akaike Information Criterion (AIC) criterion was used to select the lag combination in the study (Figure 1). AIC is the most commonly used criterion in comparing ARDL models, providing an optimal balance between fit and simplicity, and the lower its value, the better the model is considered. In this study, all possible lag combinations were automatically evaluated, and the model with the lowest AIC value was selected from a total of 100 ARDL models. This identified a model with the most statistically optimal lag structure that most accurately reflects the dynamic relationship between CO_2 emissions, economic growth, and foreign trade openness, which provides a solid basis for the reliable continuation of further analyses.

Figure 1 serves as an important visual basis for selecting the optimal lag structure. The lowest AIC value among the evaluated models corresponds to the ARDL(1,4,0) model. The remaining models are considered less statistically acceptable due

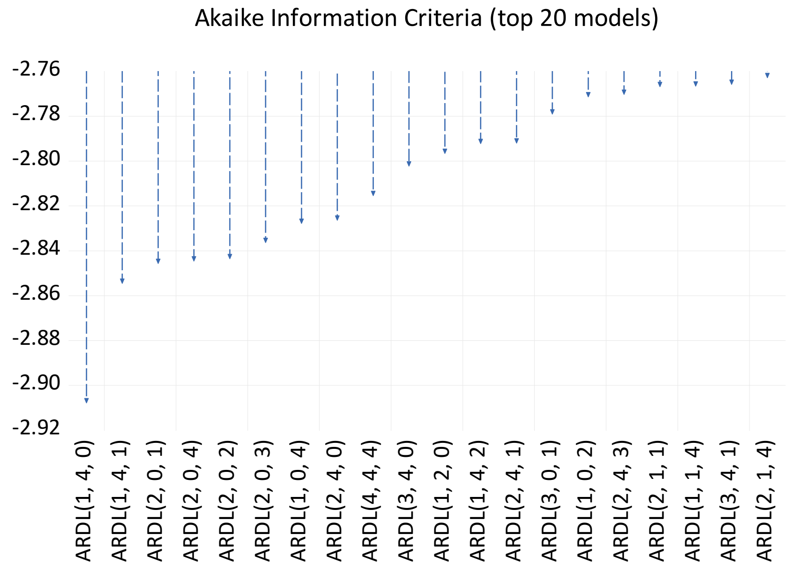

Figure 1. Model selection based on Akaike information criterion (Top 20 ARDL models)

Table 4. Estimated ARDL(1,4,0) model for CO_2 emissions with GDP and trade openness

Dependent Variable: LNCO2
Method: ARDL
Sample (adjusted): 2001 2024
Included observations: 24 after adjustments
Maximum dependent lags: 4 (Automatic selection)
Model selection method: Akaike info criterion (AIC)
Dynamic regressors (4 lags, automatic): LNGDP LNTO
Fixed regressors: C
Number of models evaluated: 100
Selected Model: ARDL(1, 4, 0)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LNCO2(-1)	0.062121	0.238997	0.259924	0.7982
LNGDP	0.049853	0.099823	0.499414	0.6243
LNGDP(-1)	−0.042138	0.172460	−0.244336	0.8101
LNGDP(-2)	−0.172435	0.155445	−1.109298	0.2837
LNGDP(-3)	0.157874	0.142196	1.110252	0.2833
LNGDP(-4)	−0.177056	0.084812	−2.087631	0.0532
LNTO	−0.173386	0.078696	−2.203231	0.0426
C	5.744175	1.474852	3.894748	0.0013
R-squared	0.917840	Mean dependent var		1.488499
Adjusted R-squared	0.881894	S.D. dependent var		0.144458
S.E. of regression	0.049645	Akaike info criterion		−2.906626
Sum squared resid	0.039434	Schwarz criterion		−2.513941
Log likelihood	42.87951	Hannan-Quinn criter.		−2.802446
F-statistic	25.53440	Durbin-Watson stat		1.803281
Prob(F-statistic)	0.000000	–		

Note: * p-values and any subsequent tests do not account for model selection.

to their relatively high AIC. The fact that the first model is located at the lowest point on the left once again confirms that the ARDL(1,4,0) combination is the best choice in terms of AIC. The selection of this model shows that CO_2 emissions respond to changes in economic growth with a four-year lag; this is consistent with the inert, i.e., slow-reacting nature of environmental processes.

Since the results of the bounds test reveal a long-run relationship between CO_2 emissions, economic growth, and foreign trade openness, the main focus of the ARDL approach is to estimate long-run elasticities. The ARDL(1,4,0) model is used at this stage based on a limited constant and trendless specification to determine the long-run impact of economic growth and foreign trade openness

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Table 5. Long-run coefficient estimates from the ARDL(1,4,0) model for CO_2 emissions

Levels Equation				
Case 2: Restricted Constant and No Trend				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNGDP	−0.196084	0.016678	-11.75699	0.0000
LNTO	−0.184870	0.055557	-3.327571	0.0043
C	6.124645	0.393153	15.57827	0.0000
$EC = LNCO2 - (-0.1961 \cdot LNGDP - 0.1849 \cdot LNTO + 6.1246)$				

on CO_2 emissions. The estimated long-run coefficients show how deeply and persistently emission indicators are related to macroeconomic factors. The results confirm that CO_2 emissions are explained by a dynamic structure that is in equilibrium with both economic growth processes and foreign trade integration. This indicates that a stable ecological-economic relationship has been formed within the economic system of Uzbekistan and creates a solid scientific basis for estimating long-run parameters.

The long-run ARDL results (Table 5) show that CO_2 emissions have a stable, statistically significant relationship with economic growth and foreign trade openness. The negative and highly significant coefficient on GDP ($\beta = -0.1961$; $p = 0.0000$) indicates that economic growth reduces emissions in the long run. This is explained by processes such as increased energy efficiency, reduced carbon intensity, and increased technological modernization. This result is consistent with the downward sloping segment of the Environmental Kuznets Curve and is consistent with empirical observations of Uzbekistan's economic modernization processes.

The negative and significant coefficient on trade openness ($\beta = -0.1849$; $p = 0.0043$) suggests that trade integration also contributes to reducing CO_2 emissions. The main reasons for this are the introduction of clean technologies through imports, increased international environmental requirements, and the need for exporters to adapt to environmental standards. This result is fully consistent with the pollution halo hypothesis, which states that trade openness contributes to environmental improvements.

The high and significant value of the constant indicates a structural baseline level of CO_2 emissions in the long run, independent of economic factors. The long-term equilibrium equation is expressed as

$$LNCO2 = 6.1246 - 0.1961 \cdot LNGDP - 0.1849 \cdot LNTO, \tag{10}$$

which shows that with a 1% increase in GDP, emissions decrease by 0.196%, and with a 1% increase in trade openness, by 0.185%. Thus, in the conditions of Uzbekistan, both economic growth and foreign trade integration have formed long-term mechanisms that reduce environmental pressure.

After confirming the existence of cointegration through the bounds test, the ARDL(1,4,0) model was transferred to estimate short-term dynamics based on the error correction mechanism. The ECM approach allows us to determine how quickly short-term fluctuations in CO_2 emissions will correct changes in economic growth and imbalances that arose in previous years. The results of the short-term estimation are presented in Table 6.

The short-run ARDL results clearly show that economic growth has a different impact on CO_2 emissions over time. The impact of the current year's economic growth is insignificant, indicating that CO_2 emissions are not sensitive to immediate changes; in the short run, internal factors such as energy prices, productivity, and technological changes neutralize this impact. However, a one-year lag in growth tends to increase emissions, indicating that emissions increase in the short run as a result of increased production and energy consumption. While the two-year lag effect is not statistically significant, a three-year lag has a significant positive coefficient, indicating that the environmental consequences of economic growth increase over time. This process implies the existence of a lagged environmental cost of economic growth and reflects the inert nature of CO_2 emissions.

Table 6. Error correction model (ECM) results for the short-run dynamics of CO_2 emissions

ECM Regression				
Case 2: Restricted Constant and No Trend				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(LNGDP)	0.049853	0.079017	0.630912	0.5370
D(LNGDP(-1))	0.191617	0.101977	1.879017	0.0786
D(LNGDP(-2))	0.019183	0.083727	0.229111	0.8217
D(LNGDP(-3))	0.177056	0.076170	2.324502	0.0336
CointEq(-1)*	–0.937879	0.200486	–4.678026	0.0003
R-squared	0.562768	Mean dependent var		–0.005941
Adjusted R-squared	0.470719	S.D. dependent var		0.062621
S.E. of regression	0.045558	Akaike info criterion		–3.156626
Sum squared resid	0.039434	Schwarz criterion		–2.911198
Log likelihood	42.87951	Hannan–Quinn criter.		–3.091514
Durbin-Watson stat	1.803281	–		

Note: * p-value incompatible with t-Bounds distribution.

As shown by the large negative and highly significant value of the ECM term (–0.937879), approximately 94% of the imbalance in the system is eliminated within one year. This indicates a high rate of return of emission processes to long-term equilibrium, confirming that the economic-ecological system has a stable and flexible structure. Thus, although economic growth may increase emissions in the short term, this negative impact will decrease over time, consistent with long-term results, and environmental pressure due to technological factors will decrease.

The short-term conclusions from the ECM results complement the long-term analysis, showing that economic growth initially increases emissions through a "scale effect", but over time, a "technical effect" increases and reduces emissions. This is consistent with the mechanism within the EKC theory.

The functional form of the model was checked using the Ramsey RESET test. The test serves to determine whether there are omitted variables or an incorrect functional form in the regression equation. The *p*-value above the 5% threshold allowed us not to reject the null hypothesis, which means that the ARDL model is correctly specified, important factors are not omitted, and the functional form is free from nonlinearity. This result increases the reliability of the short- and long-term estimates obtained from the model.

The Ramsey RESET test (Table 7) is an important diagnostic tool for assessing whether the func-

Table 7. Ramsey RESET specification test for the estimated ARDL model

Ramsey RESET Test			
Equation: UNTITLED Omitted Variables: Squares of fitted values Specification: LNCO2 LNCO2(–1) LNGDP LNGDP(–1) LNGDP(–2) LNGDP(–3) LNGDP(–4) LNTO C			
	Value	**Df**	**Probability**
t-statistic	1.838618	15	0.0859
F-statistic	3.380517	(1, 15)	0.0859
Likelihood ratio	4.877786	1	0.0272
F-test summary			
	Sum of Sq.	**Df**	**Mean Squares**
Test SSR	0.007253	1	0.007253
Restricted SSR	0.039434	16	0.002465
Unrestricted SSR	0.032182	15	0.002145
LR test summary			
	Value		
Restricted LogL	42.87951		
Unrestricted LogL	45.31840		

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tional form of an ARDL model is correctly selected. It serves to identify the presence of omitted variables or an incorrect functional form in the regression equation (Babatunde et al., 2014). The test results show that the p-value for the t-statistic and F-statistic is 0.0859, which is above the 5% confidence level but close to the 10% threshold. At the most widely used 5% threshold, the model specification is correct, the null hypothesis is not rejected, and there is no evidence of significant omissions in the ARDL equation. Although the p-value close to 10% indicates a very weak level of probability uncertainty in the functional form, the 5% threshold is considered sufficient in ecological and macroeconomic studies and does not reveal any specification error in this model.

Although the likelihood ratio test shows that the log-likelihood of the unrestricted model is higher than that of the restricted model, this difference does not affect the overall validity of the model, because the main assessment in the RESET test relies on the *F*-statistic, which confirms that the model is well-formed (Canterle & Bayer, 2015). The very small difference between the restricted and unrestricted SSR values also indicates that there are no omitted factors in the ARDL equation, and the functional form is sufficiently well constructed. Overall, the RESET test confirms the linear structure of the ARDL(1,4,0) model, providing a solid basis for the reliability of the estimated short- and long-run coefficients.

It is also important to check the stability of the error variance when assessing the quality of the model. If the error variance varies with the values of the variables, this creates a problem of heteroscedasticity, which reduces the reliability of the regression results. The Breusch–Pagan–Godfrey test tests the null hypothesis that the errors have constant variance. The general diagnostic shows that the error structure of the ARDL model is stable, confirming the usefulness of the model.

The results of the Breusch–Pagan–Godfrey test (Table 8) for heteroscedasticity showed that there was no problem with the error structure of the ARDL model (Akewugberu et al., 2024). All p-values are in the range of 0.43–0.94, which is well above the 5 or 10% significance level. This means that the null hypothesis of the test – that the errors are homoscedastic – is not rejected. Thus, the errors of the ARDL model have a constant variance and do not vary with the values of the variables. Therefore, the estimated coefficients, their standard errors, and t-statistics are reliable. The fact that all three versions of the test – the F-statistic, the LM-statistic, and the Scaled ESS – confirm the same result further reinforces the absence of heteroscedasticity in the model.

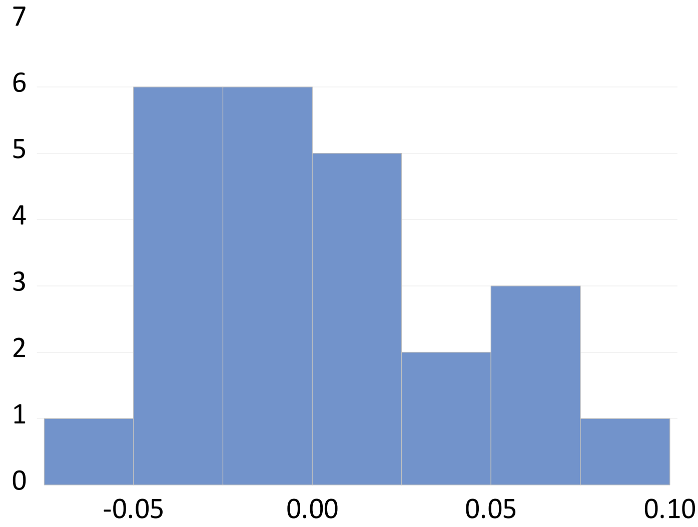
In time series models, the presence of sequential error correlation can significantly distort regression results. Autocorrelation can lead to inefficient estimated coefficients, unreliable *t*-statistics and *p*-values, and misinterpretation of overall model quality indicators (Modu & Inuwa, 2023). Therefore, to fully assess the validity of the ARDL model, the Breusch–Godfrey Serial Correlation LM test was performed (Table 9). The null hypothesis of the test is that there is no serial correlation in the model errors up to two lags; if the *p*-value is high, the null hypothesis is not rejected, and the absence of autocorrelation in the model is confirmed. This step is an important diagnostic check to determine whether the ARDL results are stable and reliable.

Table 8. Breusch–Pagan–Godfrey heteroscedasticity test for the ARDL model

Heteroskedasticity Test: Breusch–Pagan–Godfrey			
Null hypothesis: Homoskedasticity			
F-statistic	0.927357	Prob. F(7,16)	0.5119
Obs*R-squared	6.926880	Prob. Chi-Square(7)	0.4365
Scaled explained SS	2.231365	Prob. Chi-Square(7)	0.9459

Table 9. Breusch–Godfrey serial correlation LM test for the ARDL model

Breusch-Godfrey Serial Correlation LM Test:			
Null hypothesis: No serial correlation at up to 2 lags			
F-statistic	0.078516	Prob. F(2,14)	0.9249
Obs*R-squared	0.266212	Prob. Chi-Square(2)	0.8754



Series: Residuals	
Sample 2001 2024	
Observations 24	
Mean	1.22e-15
Median	-0.013109
Maximum	0.095991
Minimum	-0.064087
Std. Dev.	0.041407
Skewness	0.564879
Kurtosis	2.449591
Jarque-Bera	1.579302
Probability	0.454003

Figure 2. Histogram and Jarque–Bera normality test of residuals from the ARDL model

The results of the serial correlation assessment clearly show that there is no serial dependence in the model errors. The p-values of both tests are in the range of 0.87–0.92, which is well above their 5 or 10% significance levels, indicating that the null hypothesis is not rejected and that there is no serial correlation in the model. The independence of the errors confirms that the dynamic structure of the ARDL model is correctly chosen, the number of lags is optimal, and the short- and long-term coefficients have a reliable statistical basis. Since time series in ecological economics are often inert, in particular, CO_2 emissions move in a trend-dependent manner, the absence of the serial correlation problem is considered an important advantage of the model.

Another important diagnostic step of the ARDL model is to check whether the residual distribution is normal. A normal distribution of residuals ensures that the regression results – *t*-statistics, *F*-tests, and *p*-values – are interpreted correctly. For this purpose, the Jarque–Bera test and the residual histogram were used to visually and statistically assess the distribution properties of the model errors.

The Jarque–Bera test for normal distribution confirmed the statistical stability of the residuals obtained from the ARDL model (Figure 2). The test statistic is 1.5793 and the *p*-value is 0.4540, which is significantly higher than the 5% significance level. Therefore, the null hypothesis is not rejected and the conclusion is drawn that the residuals do not differ significantly from the normal distribution. The normal distribution of the residuals ensures that the functional form of the model is correctly specified, the parameter estimates are reliable, and the results obtained based on the *t* and *F*-statistics are scientifically consistent. In empirical studies in ecological economics, the normality condition can often be violated due to fluctuations in real data. In this sense, the normality of the residual distribution in this study indicates that the model is built with high quality and the data fit the ARDL structure well.

This positive result for the normality of the residuals, together with the heteroscedasticity and serial correlation tests, confirms that the ARDL model has successfully passed the full diagnostic tests. As a final stage of diagnostics, the CUSUM test was used to assess the stability of the model parameters over time. This test determines the degree of variability of the parameters over the entire sample based on recursive residuals. If the CUSUM line remains within the limits of the 5% confidence interval, the stability of the model parameters over time is considered to be ensured; if the line goes beyond the limits, the variability of the parameters is high, and the model may give unstable results.

The results of the CUSUM plot clearly confirm the stability of the ARDL model parameters over time. As shown in Figure 3, the blue line representing

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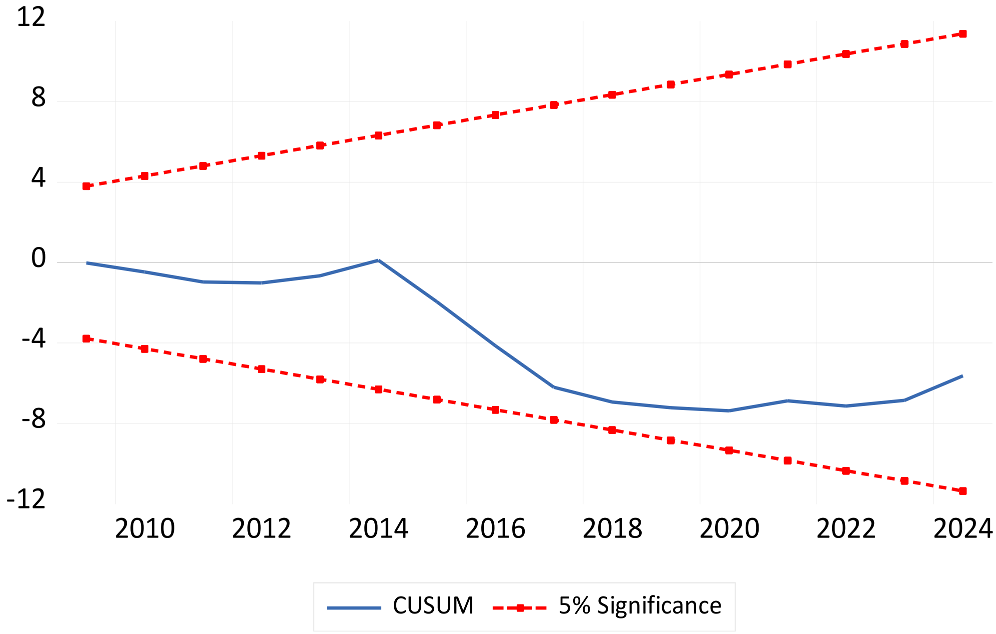

Figure 3. CUSUM stability test for the estimated ARDL model

the cumulative residual sum remained within the red dotted boundaries defining the 5% confidence interval throughout the entire observation period – from 2009 to 2024. This process means that the parameters did not undergo significant changes in the sample. Although a sharp downward trend was observed on the line between 2014 and 2018, it did not go beyond the selected critical range and indicated that the parameters maintained a consistent movement. A slight upward deviation between 2021 and 2024 also did not go beyond the limits and did not undermine the stability of the model. Thus, the parameters estimated by the ARDL model are reliable over time and structurally intact.

Such stability is very important in ecological-economic interpretation. It is natural that over time, political reforms, new economic programs, or modernization processes in the energy system lead to variability of parameters. However, the results of the CUSUM test show that the relationship between Uzbekistan's economic growth and CO_2 emissions remains in the same direction throughout the sample. Similarly, the emission-reducing effect of foreign trade openness is also stable, and the energy efficiency policies implemented in the country are reflected in the consistent movement of parameters. This shows that the ARDL model provides a reliable basis for interpreting long-term and short-term elasticities.

In general, the CUSUM test confirms that there is no structural discontinuity in the model parameters, that the ARDL model works stably throughout the sample, and that the estimated short- and long-run coefficients are consistent and reliable. The persistence of the ecological-economic relationships in the same direction over time indicates that the model has high diagnostic stability. Thus, the CUSUM test once again confirms that the selected ARDL model is fully suitable and scientifically sound for ecological interpretations.

4. DISCUSSION

The empirical findings of this study provide evidence of a stable long-run relationship between economic growth, trade openness, and CO_2 emissions in Uzbekistan. The negative long-run elasticities of both GDP and trade openness indicate that economic expansion and increasing integration into global markets are associated with declining emissions intensity over time. This result suggests that structural modernization, technological upgrading, and improvements in energy efficiency accompany economic development, supporting the environmental improvement pathway predicted by the upper stage of the Environmental Kuznets Curve (EKC). In particular, the estimated elasticities imply that income growth contributes

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to environmental performance not through reduced production activity but through efficiency gains and technological transformation.

The results also provide empirical support for the pollution halo hypothesis, according to which trade openness facilitates the diffusion of cleaner technologies and strengthens environmental standards through international market participation. This finding is consistent with previous studies that report environmentally beneficial effects of trade integration when countries adopt modern production technologies and improve regulatory frameworks (Antweiler et al., 2001; Shahbaz et al., 2014). However, the results differ from studies that confirm the pollution haven hypothesis, where trade openness increases emissions due to relocation of pollution-intensive industries (Tachie et al., 2020). One possible explanation for this difference lies in Uzbekistan's recent economic reforms, modernization policies, and increasing investment in energy efficiency and renewable energy, which may have altered the traditional scale–composition–technique balance observed in earlier developing economy studies.

The short-run dynamics reveal a more complex adjustment process. While the immediate effect of economic growth on emissions is statistically insignificant, lagged GDP effects are positive in the short term, indicating that economic expansion initially increases energy demand and emissions through a scale effect before technological improvements materialize. This temporal pattern aligns with theoretical expectations from EKC-related models, where environmental pressures rise during early development phases and decline as economies transition toward more efficient production structures. The large and statistically significant error correction coefficient further indicates a rapid adjustment toward long-run equilibrium, suggesting that structural factors dominate temporary fluctuations in emissions.

From a theoretical perspective, the findings contribute to the literature on the trade–environment nexus in transition economies by demonstrating that the relationship between trade openness and environmental outcomes is context-dependent and influenced by institutional reforms, technological adoption, and structural transformation. The results highlight that trade integration alone does not determine environmental outcomes; rather, the interaction between trade policies, technological modernization, and domestic regulatory capacity shapes the environmental trajectory of economic growth. This insight is particularly relevant for economies undergoing systemic transformation, where policy sequencing and institutional quality play critical roles.

The practical implications of the results are significant for policymakers. The observed emissions-reducing effect of trade openness suggests that continued integration into international markets, including WTO accession processes, may support environmental sustainability if accompanied by policies promoting energy efficiency, technological upgrading, and environmental standards compliance. Expanding investments in renewable energy, strengthening environmental certification systems for export-oriented industries, and encouraging green technological diffusion through foreign trade and investment channels could reinforce the long-run environmental benefits identified in this study. At the same time, the short-run emission increases associated with economic growth underline the importance of proactive environmental regulation and monitoring during periods of rapid industrial expansion.

Despite these contributions, the study has several limitations. First, the analysis uses aggregate trade openness indicators and does not distinguish between exports and imports or sectoral trade composition, which may have heterogeneous environmental effects. Second, the model does not explicitly incorporate energy structure variables, foreign direct investment, or technological innovation indicators that could further explain emissions dynamics. Third, the country-specific focus limits the generalizability of the findings across regions with different institutional and energy characteristics. Future research could extend this analysis by incorporating sector-level trade data, renewable energy indicators, or nonlinear modeling approaches such as NARDL to examine potential asymmetries in the growth–environment relationship. Comparative studies across Central Asian economies would also provide valuable insights into regional environmental–economic interactions.

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Overall, the results indicate that Uzbekistan's economic growth and trade integration processes are not inherently incompatible with environmental sustainability. Instead, when supported by technological modernization and institutional reforms, trade openness may contribute to reducing carbon intensity and promoting a transition toward a more sustainable development trajectory.

CONCLUSION

This study examined the relationship between economic growth, trade openness, and CO_2 emissions in Uzbekistan using the ARDL bounds testing approach with annual data for 1997–2024. The results reveal that both GDP growth and trade openness reduce emissions in the long run, supporting the pollution halo hypothesis, while short-run dynamics indicate temporary emission increases associated with lagged economic expansion. The high error correction coefficient confirms rapid adjustment toward long-run equilibrium, suggesting that structural factors dominate short-term fluctuations.

These findings imply that Uzbekistan's ongoing economic modernization and trade integration, including WTO accession efforts, can be compatible with environmental sustainability if supported by technological upgrading, energy efficiency policies, and strengthened environmental regulations. Overall, the study provides empirical evidence that trade-driven growth does not necessarily increase environmental pressure and may instead contribute to a transition toward lower carbon intensity development.

AUTHOR CONTRIBUTIONS

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Writing – review & editing: Zebo Tukhtaeva, Fozil Xolmurotov, Fakhridin Karshiev, Xolilla Xolmuratov.

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