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Investigating the Link Between Trade Openness and Environmental Degradation: The Case of the Organization of Turkic States

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Abstract

In an era of rapidly expanding global trade, the environmental costs of trade openness (TO) are a crucial area of study in relation to sustainable development goals. This study investigates the link between TO and environmental degradation by analysing the carbon emission patterns of five developing Organization of Turkic States (OTS) members. This study employs panel data methods over the period 1993–2021 and includes economic growth (EG) and renewable energy consumption (REN) as control variables. The panel cointegration test results verify that the TO, EG, REN, and CO_2 have a long-term relationship. According to the AMG and CCEMG estimation results, TO has a significant and positive long-term impact on CO_2 emissions. This finding implies that trade liberalisation causes environmental degradation in the context of OTS countries through scale effects, and it provides empirical evidence for the Pollution Haven Hypothesis (PHH). On the other hand, the analysis illustrates that REN decreases CO_2 emissions, highlighting the importance of the energy transition to maintain environmental sustainability. The results emphasise the need to design trade policies in OTS countries with regard to the environment. Under these circumstances, it is recommended to integrate trade policies with environmental regulations, to promote and adopt green technologies for renewable energy and production, and to strengthen environment-focused regional trade cooperation mechanisms in the OTS countries.

Keywords Trade Openness · CO_2 Emissions · Environmental Degradation · Organization of Turkic States · Panel Data Analysis

JEL Classification C33 · Q50 · Q56

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Investigating the Link Between Trade Openness and Environmental Degradation: The Case of the Organization of Turkic States

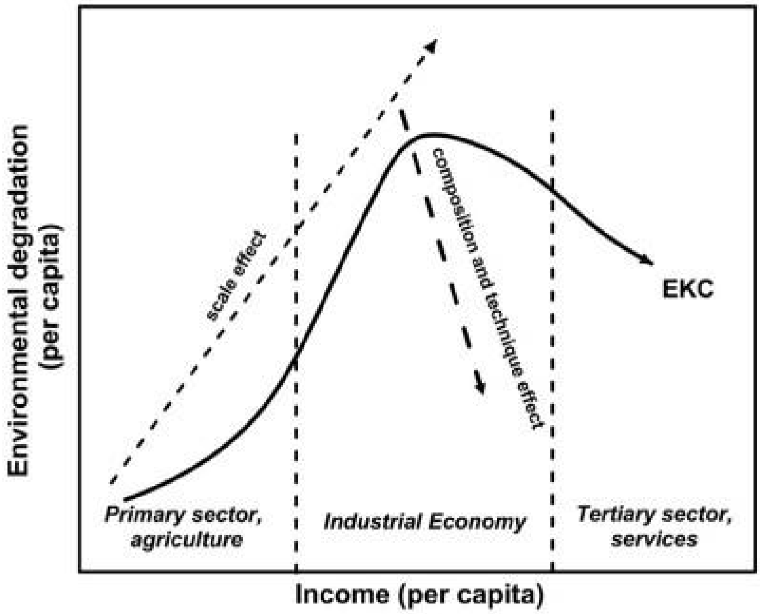
Environmental pollution, environmental quality, and environmental degradation are among the frequently studied topics within the concept of sustainability. Researchers focusing on sustainability perform analyses by taking into account numerous variables associated with environmental pollution and climate change. While the effects of many factors are examined in the emergence of environmental problems, the well-known main reason is carbon-intensive energy consumption. Energy consumption causes air, soil and water pollution by creating greenhouse gas (GHG) emissions. Although the improvement of renewable energy systems developed with new investments continues, fossil fuels accounted for 81.5% of the primary energy consumption in 2023 (Energy Institute, 2024). The challenges that countries face in shifting their energy policies, especially in terms of costs, reconstruction and transformation, point out that increasing the use of renewable energy may take many years. At present, total energy consumption is still dominated by fossil fuel-based energy sources. In addition, the use of fossil fuels, which are among the factors that affect environmental sustainability, is directly related to EG. In countries where economic activities are increasing, energy is used as an important production input and gradually more energy is consumed (Jeon, 2022). As a result, models are built using different variables to determine the factors that cause CO_2 emissions, which have a significant share in GHG emissions. A range of explanatory variables— including foreign direct investment (FDI), agricultural value-added, TO, urbanisation, population, agricultural land, financial development, and deforestation—are examined in the studies for their effects on GHG emissions in terms of CO_2 amount. In these studies, CO_2 emission was frequently used as an endogenous variable to proxy for GHG emissions.

Economic activities and growth are important pollution factors that are addressed in studies on environmental issues. The Environmental Kuznets Curve (EKC) hypothesis is commonly employed to explore the link between economic development and environmental degradation. Initially introduced by Kuznets (1955) in the context of income inequality and EG, the concept was later adapted by Grossman and Krueger (1991) to examine environmental concerns (Baajike et al., 2024). Under the EKC, an inverted U-shaped relationship exists between EG and environmental degradation. According to the hypothesis, resource exploitation during the early phases of development leads to more pollution. However, once a country's per capita income reaches a certain level (a turning point), environmental pollution starts to decrease as the economy grows (Bölük & Mert, 2015).

Economic development and the environment interact through scale, technique, and composition effects (Grossman & Krueger, 1991). In the early phases of EG, rapidly increasing economic activities and the excessive use of natural resources increased pollution. As output increases, the demand for inputs and natural resources correspondingly rises. Consequently, this process generates more waste and GHG emissions, intensifying environmental degradation. This effect is known as the scale effect. The increase in industrial production leads to an upward trend in the EKC. Transformations in the production structure in line with economic development are expected to have a positive impact on the environment under the composition effect. Increase in income changes the structure of the economy and enables the development of production knowledge that emits less pollution, improvement of production techniques and adoption of cleaner technology. The demand for environmental sustainability tends to grow alongside income. A developed country has the opportunity to invest more in research and development. With technological development, EG has led to new environmentally friendly technology that enhances environmental quality. This is called the technique effect (Dinda, 2004).

Figure 1

Scale, Composition and Technique Effect on the EKC



Source: Kaika & Zervas, 2013

In terms of the components of the EKC, commercial activities interact with the environment. Although globalisation encompasses various definitions, it broadly refers to a world characterised by increased accessibility to FDI and international trade, emphasising trade and financial liberalisation. The *scale effect* explains how trade affects production levels, while the *composition effect* captures how a country's production structure interacts with its TO. Depending on their stage of development, developing countries may rely more on pollution-intensive production techniques, whereas developed countries are more likely to adopt cleaner and more sustainable methods (Dinda, 2004). Industrialisation represents a transition from agriculture to manufacturing, implying larger-scale production, increased TO, and higher energy use. There is a conflict between the dependence on traditional energy sources to meet humanity's growing energy demand and the need for clean energy at a time of rising environmental concerns. The demand for energy inputs and the increasing global trade in energy also influence the path of industrialisation (Wang et al., 2023). TO, energy consumption, and economic development are the interacting factors of GHG emissions. As the EKC provides a general framework for studies examining environmental degradation in relation to these determinants, it serves as a key overarching hypothesis.

The increasing openness of economies and their growing interaction with the world under the influence of globalisation have drawn significant attention to environmental issues. One of the well-known theories regarding the environmental impact of trade activities is the PHH. This hypothesis posits that multinational corporations engaged in pollution-intensive production may relocate their operations to developing countries because environmental regulations in developed countries are strict, thereby increasing the pollution levels in the host countries. Since greater TO is typically associated with increased international trade and FDI, it is often assumed that such openness may lead to higher levels of environmental pollution (Ren et al., 2014). However, some studies argue that in certain countries, the pressure of global competition may lead to more efficient resource use, suggesting that increased TO could also contribute to a reduction in pollution (Cole, 2004). Thus, there is evidence supporting both the pollution-increasing and the pollution-reducing effects of TO. Another perspective related to the subject is the Porter Hypothesis, which point out that strict environmental regulations may influence energy resource management and promote the development of environmentally friendly systems, including renewable energy. While restrictive environmental policies impose financial burdens on firms, the hypothesis argues that such regulations may in fact enhance firms' competitiveness and productivity. Moreover, it provides motivation for the advancement of green technologies (Xuan, 2025).

The member states—Azerbaijan, Kazakhstan, the Kyrgyz Republic, Uzbekistan, and Türkiye—have attracted increasing attention due to their expanding commercial and economic activities. With the exception of Türkiye, the member countries are former Soviet Union (FSU) states, characterised by their substantial endowment of traditional underground resources and use these resources for their economic development. These countries, located in Central Asia and the Caucasus, play an important role in the global energy markets. However, their extensive reliance on fossil-based resources has led to significant environmental issues (Faizi et al, 2024). An example of regional cooperation is the adoption of the OTS Trade Facilitation Strategy by the heads of the Turkic States during the 9th Summit, held in Samarkand on 11 November 2022. In accordance with this strategy, the Trade Facilitation Committee (TFC) was established within the OTS framework. The TFC has been tasked with facilitating trade processes among Turkic states, reducing trade barriers, and creating a more conducive environment for trade (Organization of Turkic States, 2025). Additionally, the member countries possess energy markets that remain highly dependent on fossil fuels. According to World Bank data, as of 2022, fossil fuels made up 81.8% of the final energy consumption in Türkiye, 98.2% in Kazakhstan, 98.4% in Uzbekistan, 72.9% in the Kyrgyz Republic, and 100% in Azerbaijan (World Bank, 2025). These countries have experienced rising CO_2 emissions in recent years due to the increased energy demand for economic development. A comparison of the period between 2013 and 2023 shows that energy-related CO_2 emissions increased by 3.1% in Türkiye, 0.5% in Kazakhstan, 0.9% in Uzbekistan, and 3.4% in Azerbaijan. These figures indicate that, with the exception of Kazakhstan, all member states experienced CO_2 emission growth rates above the world average increase of 0.7% (Energy Institute, 2024).

This study consists of five sections. The first section introduces the theoretical framework. The second section includes a literature review. The third section outlines the dataset, econometric model, and methodology. The fourth section includes the analysis results and discusses the findings. The last section provides the conclusion and policy recommendations.

Literature Review

There has been considerable attention in research focusing on the Sustainable Development Goals in recent times. Particularly under current global conditions, where environmental degradation poses a serious concern to the future of the planet, an increasing number of academic research has aimed to identify the key determinants of environmental degradation. The growing emphasis on global cooperation has increasingly led scholars to examine the country-specific contributions to environmental damage.

This study encompasses three explanatory variables: EG, REN, and TO. Regarding the relationship between EG and GHG emissions, most existing studies aim to validate the EKC hypothesis for selected countries or regions. The hypothesis stems from the inverted U-shaped pattern proposed by Kuznets (1955), which originally illustrated the income-inequality relationship. In its later form, the EKC indicate that EG influences environmental degradation in a non-linear path. From an empirical perspective, several studies —including those by Apergis & Payne (2009), Cole et al. (1997), Du et al. (2022), Grossman & Krueger (1991), Heidari et al. (2015), Jeon (2022), Naseem et al. (2024), and Selden & Song (1994)—have validated the EKC hypothesis. Conversely, studies such as Akbostanci et al. (2009), Dinda & Coondoo (2006), Holtz-Eakin &

Selden (1995), Shafik (1994), and Timmons Roberts & Grimes (1997) do not find supporting evidence for the existence of the EKC. Moreover, when analysing the relationship between EG and environmental degradation, different results can be obtained depending on the stage of the countries on the EKC. Du et al. (2022) found that EG in China led to higher levels of environmental pollution, which reflects the dominance of the scale effect during the study period. Naseem et al. (2024), analysing G20 countries from 1990 to 2020, found that EG had a mitigating effect on CO_2 emissions. This indicate that, during the study period, the G20 economies had progressed beyond the turning point. In the literature, the empirical validation of the existence and relevance of the EKC hypothesis constitutes a central line of inquiry. As previously mentioned, the EKC stands as a foundational and overarching hypothesis at the core of the debate concerning the relationship between EG and environmental degradation.

In examining the relationship between EG and environmental degradation, variables such as fossil fuel-based energy consumption and REN—either individually or jointly—are among the most commonly used indicators providing insights into energy use. The fact that fossil fuel use contributes to environmental degradation is widely acknowledged and often considered a real-world observation that requires no further empirical proof. What is crucial, however, is the search for viable alternatives. In this context, increasing REN —often referred to as clean and environmentally friendly energy sources—has become an environmental necessity. Nevertheless, renewable energy is frequently included as a control variable in empirical studies. For instance, Le (2022) found that although non-renewable energy use may contribute to EG, it simultaneously leads to environmental degradation. Conversely, the study confirms that increased REN has a mitigating effect on CO_2 emissions and, by extension, environmental degradation. Similarly, Ashraf et al. (2023) found that REN, including its spatial spillover effects, is negatively associated with CO_2 emissions, indicating an inverse relationship. Several studies including Ali & Kirikkaleli, 2022; Bilgili et al., 2016; Bölük & Mert, 2015; Jeon, 2022 also offer evidence supporting the positive contribution of REN in promoting environmental quality.

Finally, this study also reviews the literature on the environmental implications of trade activities and TO, which constitute one of the main elements of the analysis. In this context, there are empirical studies indicate that TO may either increase or reduce CO_2 emissions. For instance, Kalmaz and Kirikkaleli (2019) found that there is a long-run relationship between TO, urbanisation, EG and energy consumption and CO_2 emissions in their study for Turkey. Hossain (2011) found causality from EG and TO to CO_2 emissions in the short run. Ren et al. (2014) found that the widening trade deficit in China served as a major driver of rapidly rising GHG emissions, and further noted that increases in FDI also intensified GHG emissions. Wang et al. (2023) observed that trade activities and production growth contributed to environmental degradation in the G7 countries. Karimi Alavijeh et al. (2023) employed panel quantile regression to analyse the impact of EG, agricultural value-added, energy consumption, total population, and TO on CO_2 emissions for the 15 developing countries with the highest population over the period 2004–2020. Their findings revealed that the effects varied across the lower and higher quantiles. Compared to other factors, TO has the strongest effect on CO_2 emissions. Ashraf et al. (2023) examined the impact of TO, REN, natural gas consumption, and EG on CO_2 emissions in 75 Belt and Road Initiative (BRI) countries from 1990 to 2019 using spatial panel data models. The findings indicated that TO, along with its spatial spillovers, positively influenced CO_2 emissions.

Several studies present mixed findings concerning the link between TO and environmental quality. Copeland and Taylor (1994) modelled two countries engaged in the production of goods with different pollution intensities and argued that high-income countries, equipped with stronger environmental regulations, tend to specialise in cleaner goods. When considered independently of the EKC hypothesis, international trade is generally found to increase pollution levels. Managi et al. (2009) investigated the LİNK between TO and environmental quality, concluding that TO improved environmental conditions in OECD countries while worsening them in non-OECD nations. Le et al. (2016) found that increasing TO on a global scale leads to environmental degradation. A noteworthy aspect of their findings is that while TO improves environmental quality in high-income countries, it worsens them in middle- and low-income countries. These results support the widely held view that wealthy nations tend to impose the environmental costs of pollution on poorer nations. Ghazouani (2025) analysing 26 countries within the BRI, found that TO initially elevates emissions but later exhibits a decreasing effect at higher quantiles, indicating a transition to greener technologies in developed economies.

Finally, several studies provide evidence supporting the view that TO can positively affect environmental quality. Shahbaz et al. (2013), in their study on Indonesia, found that TO contributes to improvements in environmental quality, with increased international trade being associated with reductions in CO_2 emissions. Similarly, Akın (2014) analysing a sample of 85 countries and found that TO contributes to reducing CO_2 emissions. Shu et al. (2025), based on Chinese firm-level data from 1999 to 2007, showed that TO in services effectively reduces emission intensity stemming from the manufacturing sector.

Data, Model, and Methodology

This study investigates the impacts of TO on carbon emissions based on the frameworks of the EKC and PHH. The analysis covers the period 1993-2021 for the OST members, namely Azerbaijan, Kazakhstan, the Kyrgyz Republic, Uzbekistan and Türkiye for which data are available. There are several noteworthy reasons for focusing the analysis on the OTS member countries. All five countries are classified as developing economies with middle-income status (IMF, 2023; World Bank, 2023). It is stated that fossil fuel use plays a major component role in their economic activities and this puts considerable pressure on environmental conditions (Faizi et al., 2024). In addition, agreements such as the Sustainable Development Goals, the Paris Agreement, and the Kyoto Protocol, to which these countries are parties or signatories, include commitments to reduce GHG emissions within a specified timeframe. Besides, under the institutional framework of the OTS, there are established goals and plans aimed at enhancing economic, trade, and environmental cooperation among member states (Organization of Turkic States, 2025; Sandalcılar & Cihan, 2023). Considering their level of development, emission trends, and cooperation-based targets, it is argued that identifying the role of trade in shaping CO_2 emissions in these countries is critical for understanding the current environmental challenges and drawing meaningful implications for the future.

The total CO_2 emissions (in metric tons), excluding emissions from land use, land-use change, and forestry (LULUCF), are employed as the dependent variable to represent carbon emissions. The explanatory variable, TO, is measured as the ratio of merchandise trade (exports and imports) to gross domestic product (GDP). The analysis also includes two additional control variables: real GDP (constant 2015 US$) to represent EG and the share of REN in total final energy consumption to capture the role of renewable energy. The dataset is compiled entirely from the World Development Indicators (WDI) provided by the World Bank (World Bank, 2025). The definitions and sources of the variables are presented in Table 1.

Table 1

Data description

Variable	Definition	Source
CO_2	Carbon dioxide emissions excluding LULUCF (Mt CO_2e)	WDI
GDP	Gross domestic product (constant 2015 US$)	WDI
REN	Renewable energy consumption (% of total final energy consumption)	WDI
TO	Merchandise trade (% of GDP)	WDI

Figure 1 presents the historical trends of CO_2 emissions (CO_2), GDP, REN, and TO in the member countries of the OTS over the period 1993–2021. It is observed that the member countries follow a similar ranking in terms of both CO_2 and GDP. Türkiye holds the highest levels of CO_2 emissions (460.65 metric tons) and GDP (US$ 1.13 trillion), followed by Azerbaijan, Kazakhstan, Uzbekistan, and the Kyrgyz Republic, respectively. Regarding the trajectory of CO_2 emissions, Türkiye has demonstrated a steadily increasing trend in emissions over time compared to the other member countries. A similar observation can be made for EG, as Türkiye has achieved relatively higher growth rates and has widened its income gap with the other countries over the years. Considering the share of REN in total final energy consumption, the Kyrgyz Republic stands out with the highest share (27.6%) among the member states. Türkiye ranks second with a renewable energy share of 12%, which is less than half of the Kyrgyz Republic's share. Azerbaijan, Kazakhstan, and Uzbekistan, on the other hand, exhibited relatively low levels of REN. A similar pattern is observed in the trade intensity. The Kyrgyz Republic ranks first, with merchandise trade intensity reaching approximately 90%, indicating a highly open to trade. Azerbaijan, Türkiye, Kazakhstan, and Uzbekistan follow the Kyrgyz Republic, respectively.

Figure 2

Historical trends of the variables in the member countries of the OTS

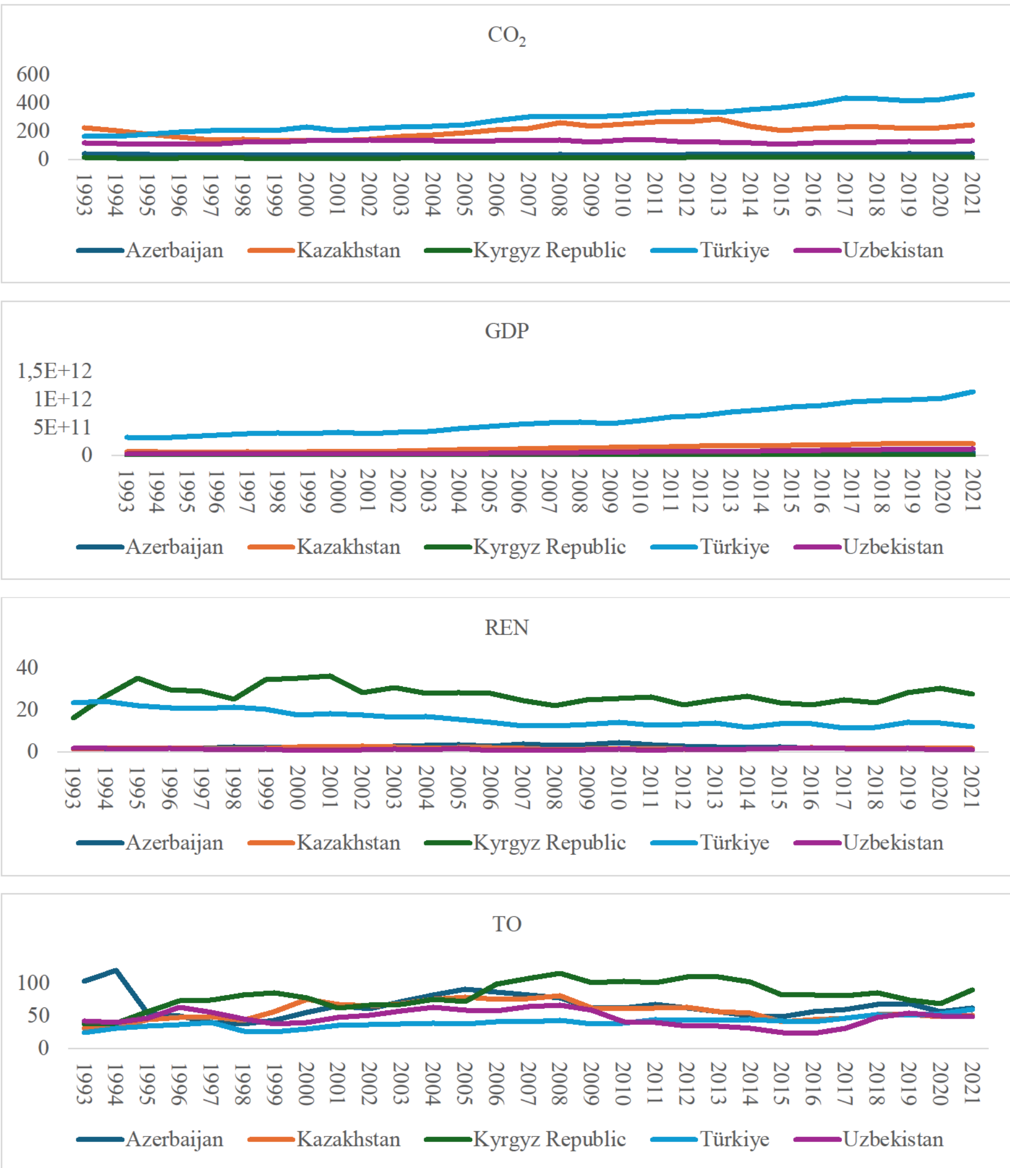


Table 1 and Table 2 present the descriptive statistics and the correlation matrix of the variables, respectively. The median values for the variables lnCO_2, lnGDP, lnREN, and lnTO were 4.812, 24.705, 0.875, and 4.020, respectively. The minimum value for lnCO_2 is 1.394, observed in the Kyrgyz Republic, while the maximum value is 6.133, recorded in Türkiye. For lnGDP, the minimum value is 21.708 for the Kyrgyz Republic, and the maximum value is 27.755 for Türkiye. The minimum value for lnREN is −0.357, corresponding to Uzbekistan, whereas the maximum value is 3.584, recorded in the Kyrgyz Republic. For lnTO, the minimum value is 3.160 for Uzbekistan, while the maximum value is 4.788 for Azerbaijan.

Table 2

Descriptive statistics

Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Observations
lnCO_2	4.230	4.812	6.133	1.394	1.374	145
lnGDP	24.687	24.705	27.755	21.708	1.673	145
lnREN	1.521	0.875	3.584	−0.357	1.274	145
lnTO	4.006	4.020	4.788	3.160	0.358	145

According to the correlation matrix, GDP is positively and strongly associated with CO_2 emissions, whereas REN and TO show negative correlations with emissions.

Table 3

Correlation matrix

Variable	lnCO_2	lnGDP	lnREN	lnTO
lnCO_2	1.000			
lnGDP	0.917	1.000		
lnREN	-0.424	-0.152	1.000	
lnTO	-0.585	-0.569	0.151	1.000

Within the framework of the analysis, following the studies of Ali & Kirikkaleli (2022), Al-Mulali et al. (2015), Dogan & Seker (2016) and Pata et al. (2023), a functional model was constructed as follows:

$$CO_{2it} = f(GDP_{it}, REN_{it}, TO_{it}) \quad (1)$$

Accordingly, the econometric model derived from Equation (1) is expressed as follows:

$$lnCO2_{it} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnREN_{it} + \beta_3 lnTO_{it} + \varepsilon_{it} i : 1, 2, ..N \ and \ t : 1, 2, ..T \quad (2)$$

In Equation (2), CO_2 is carbon dioxide emissions; GDP is economic growth; REN is renewable energy consumption; and TO is trade openness. β_0 is the constant term, and ε denotes the error term. The subscript *i* represents each country in the panel, while *t* denotes the time dimension. The natural logarithms of the variables are taken, and *ln* indicates that the variables are included in the analysis in their logarithmic forms. Economic activities, as represented by GDP, constitute a key determinant of environmental degradation and are widely recognised as a primary factor in numerous empirical analyses (Bilgili et al., 2016; Bölük & Mert, 2015; Hossain, 2011; Pata et al., 2023; Shahbaz et al., 2013). The effect of economic activity on the environment is likely to vary according to the stage of development of each country. The EKC hypothesis indicates that during the initial phases of development, EG and high energy consumption typically lead to increased environmental pollution. However, at higher income levels, increased environmental consciousness and a stronger demand for sustainability encourage stricter environmental policies and the use of cleaner technologies, which contribute to a decline in pollution levels (Dinda, 2004; Grossman & Krueger, 1991; Suri & Chapman, 1998). Given that the countries in the study are classified as developing economies, the effect of GDP on CO_2 emissions is expected to be positive ($\frac{\partial GDP}{\partial CO_2} > 0$). REN plays a compensatory role in mitigating the environmental degradation caused by intensive economic activities and fossil fuel consumption. Accordingly, enhanced REN enable the adoption of environmentally friendly technologies and foster sustainable energy practices, which help mitigate pollution (Jeon, 2022; Khan et al., 2020). Within the framework of the SDGs, REN is not only involved in advancing the global energy transition but also a critical component in enhancing energy efficiency, particularly in countries heavily dependent on fossil fuel imports (Xuan, 2025). Moreover, evidence suggests that the pollution-mitigating effects of REN are more intensely observed in countries with relatively higher income levels, stronger institutions, and have crossed a threshold in terms of REN (Chen et al., 2022). This highlights the long-term sustainable benefits of renewable energy. Therefore, due to its environmental quality-enhancing effects, the effect of REN on CO_2 emissions is expected to be negative ($\frac{\partial REN}{\partial CO_2} < 0$).

The focus of the study is the effect of TO on CO_2 emissions in the OTS countries. International trade affects environmental pollution through changes in economic activity. Within the framework of the EKC hypothesis, the link between trade, EG, and pollution emerges through three effects: *scale, composition,* and *technique effects* (Antweiler et al., 2001; Cole, 2004; Dinda, 2004; Grossman & Krueger, 1991). The scale effect implies that increased economic activity due to trade liberalisation and entry into new markets will lead to higher energy consumption and worsen environmental quality. The composition effect emphasises that trade will shape the production structure of countries according to their comparative advantage and will have an impact on the environment depending on the factor endowment and production technologies of the countries. Therefore, the environmental effect of trade varies depending on the sectors in which countries specialise. To put it another way, comparative advantage is a crucial factor in directing pollution patterns. The technique effect highlights how trade can promote the use of cleaner production processes and green technologies, thereby helping to reduce pollution. As income levels rise, public demand improves environmental conditions, which encourages the enforcement of tighter environmental standards and drives innovation in cleaner technologies that help mitigate environmental degradation. Consequently, both the development status of countries and the strength of their environmental regulations significantly influence how trade affects the environment (Cherniwchan et al., 2017; Copeland & Taylor, 1994; Grossman & Krueger, 1991; Mani & Wheeler, 1998; Shahbaz et al., 2017; Sharma, 2011). On the other hand, the PHH indicates that variations in environmental policy stringency may result in pollution-intensive industries relocating from countries with strict regulations to those with relatively more flexible or inadequate environmental policies. Accordingly, trade expansion may result in increased environmental degradation in countries with weaker environmental governance, while pollution may decline in countries with stricter regulations (Cherniwchan et al., 2017; Copeland & Taylor, 1994; Dinda, 2004; Kearsley & Riddel, 2010). However, the long-term increase in the demand for environmental quality resulting from economic development will give rise to a focus on environmental policies and new technologies. Therefore, the PHH effect may be temporary (Cole, 2004; Mani & Wheeler, 1998). Another approach to the trade-environment nexus is the Porter Hypothesis. According to this approach, stringent environmental regulations will increase productivity and competitiveness by encouraging firms to develop innovative and clean technologies beyond the cost increases they cause on production (Frankel & Rose, 2005; Xuan, 2025). Taken together, it is not entirely clear how environmental pollution will evolve in countries with high levels of trade intensity. Nevertheless, considering that the countries in the analysis are developing economies with high fossil fuel consumption, the expected impact of TO on CO_2 emissions is positive ($\frac{\partial TRADE}{\partial CO_2} > 0$).

The empirical analysis conducted within the scope of this study consists of five main stages. In the first stage, cross-sectional dependence (CSD) tests were employed to detect the presence of correlation across units. CSD implies that a shock occurring in one unit may affect other units as well. CSD may arise from interactions across units or from unobserved common factors or shocks. Neglecting CSD in panel data analysis can result in biased parameter estimates and a loss of estimation efficiency (Baltagi et al., 2012). Considering macroeconomic variables such as economic activity and international trade, the resulting cross-country linkages make CSD the rule rather than the exception (Westerlund & Edgerton, 2008). In this context, to examine whether CSD exists among the variables, Breusch & Pagan (1980) LM test, Pesaran (2004) CD and scaled LM tests, and the bias-corrected scaled LM test by Baltagi et al. (2012) were employed. These tests share a null hypothesis that assumes the absence of cross-sectional correlation across units.

In the second stage, Pesaran & Yamagata (2008) test was applied to assess the slope homogeneity across the panel. Due to the unique structural characteristics of individual countries, the slope coefficients may not be homogeneous. Therefore, determining whether the panel exhibits slope homogeneity or heterogeneity is essential for selecting the appropriate estimation technique. Within the test framework, two test statistics, $\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$, are computed. Under the null hypothesis, the slope coefficients are assumed to be homogeneous, whereas the alternative hypothesis indicates that the slope coefficients are heterogeneous. To test for unit roots in the variables during the third stage, the cross-sectionally augmented Dickey-Fuller (CADF) test introduced by Pesaran (2007) was employed, as it accounts for cross-sectional dependence. Within this framework, the cross-sectionally augmented IPS (CIPS) statistic, calculated by averaging the t-statistics obtained from CADF regressions estimated for each cross-section (unit), represents the overall panel result. Cross-sectional dependence is eliminated by augmenting the standard ADF regression with cross-sectional means and their first differences (Baltagi, 2021). The test's null hypothesis states that the variables are non-stationary.

In the fourth stage, Westerlund & Edgerton (2007) LM bootstrap co-integration test was employed to examine the long-run relationships among the variables. Its advantages include accounting for cross-sectional dependence, allowing for heterogeneity, and performing well with small sample sizes. The test is based on McCoskey & Kao (1998) LM test with a sieve bootstrap approach. The calculation of the test statistic is given by

$$LM_N^{+} = \frac{1}{NT^2}\Sigma_{i=1}^{N}\Sigma_{t=1}^{T}\hat{w}_i^{-2}S_{it}^2 \tag{3}$$

In Equation (3), $\hat{w}_i^{-2}$ is the long-run variance of the error term, while S_{it}^2 is the partial sum process of the residuals. The null hypothesis of the test states that co-integration exists for all panel units, whereas the alternative hypothesis indicates that co-integration does not exist for at least one cross-section.

In the final stage, long-run coefficient estimations were employed using the augmented mean group (AMG) estimator proposed by Eberhardt & Bond (2009) and Eberhardt & Teal (2010) and the common correlated effects mean group (CCEMG) estimator proposed by Pesaran (2006). The AMG estimator addresses the cross-sectional dependence by incorporating a common dynamic effect parameter into the error correction model, estimated for each unit in a two-step approach. In the first step, we estimate the following model by including time dummy variables:

$$\Delta y_{it} = b'\Delta x_{it} + \Sigma_{t=2}^{T}c_t D_t + e_{it} \qquad \hat{c}_t \equiv \hat{\mu}_i \tag{4}$$

In the second step, $\hat{\mu}_i$ is included in the model for each cross-sectional unit, and the AMG estimator is derived as follows:

$$\hat{b}_{AMG} = N^{-1}\Sigma_i^N\hat{b}_i \tag{5}$$

In the CCEMG estimation method, the cross-sectional averages of the variables are included in a heterogeneous panel error correction model to capture unobserved common factors. The model is estimated using the ordinary least squares (OLS) method as follows:

$$y_{it} = \alpha_{i1} + \beta_i x_{it} + \delta_i \overline{y}_{it} + \gamma\overline{x}_{it} + \theta_i f_t + \varepsilon_{it} \tag{6}$$

where f_t represents unobserved common factors. The CCEMG estimator is then calculated by taking the average of the individual CCE estimates across units:

$$\hat{b}_{CCEMG} = N^{-1}\Sigma_i^N \hat{b}_i \quad (7)$$

Both the AMG and CCEMG estimators are efficient under cross-sectional dependence, heterogeneity, and small sample sizes.

Results and Discussion

Within the scope of the analysis, first of all, it is tested whether the variables are cross-sectionally dependent or not. According to the CSD test results presented in Table 4, the null hypothesis was rejected for all variables except for the CD test result of the lnREN variable. These findings indicate the presence of cross-sectional dependence among the variables lnCO_2, lnGDP, lnREN, and lnTRADE, implying that there is a correlation across the panel units for these variables.

Table 4

CSD test results

Variables	Breusch-Pagan LM	Pesaran-scaled LM	Bias-corrected scaled LM	Pesaran CD
lnCO_2	79.190***	15.471***	15.382***	6.332***
lnGDP	272.717***	58.745***	58.656***	16.511***
lnREN	21.653**	2.606***	2.516**	−0.610
lnTO	30.095***	4.493***	4.404***	3.015***

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

As shown in Table 5, the results of the slope homogeneity test reject the null hypothesis, indicating heterogeneity in the slope coefficients across the panel. Considering the existence of both cross-sectional dependence and slope heterogeneity, it is decided to apply the Pesaran (2007) CIPS unit root test.

Table 5

Slope homogeneity test results

Model	Δ	Δ_{adj}
lnCO_2=f(lnGDP, lnREN, lnTO)	12.574***	14.185***

*** indicates significance at the 1% level.

According to Table 6, all series are non-stationary at levels and only become stationary after first-order differencing, based on the CIPS unit root test.

Table 6

CIPS unit root test results

Variables	Level	First Difference
lnCO_2	-2.333	-3.637***
lnGDP	-2.605	-4.129***
lnREN	-2.236	-5.391***
lnTO	-2.426	-3.942***

*, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively. The critical values are 3.12 for the 1% level, 2.87 for the 5% level, and 2.73 for the 10% level.

Given the results of the diagnostic tests, Westerlund & Edgerton (2007) LM bootstrap cointegration test was employed to analyse the long-run relationship among the variables, taking into account cross-sectional dependence, heterogeneous slope coefficients, and non-stationarity. Table 7 presents both the asymptotic and the bootstrap p-values (accounting for cross-sectional dependence). As cross-sectional dependence is present, the bootstrap p-value is decisive. Because the null hypothesis of no co-integration cannot be rejected, this supports the presence of a long-run relationship among the variables. Accordingly, the long-run coefficients were estimated using the AMG and CCEMG estimators. The estimation results are presented in Table 8.

Table 7

LM bootstrap co-integration test results

LM Bootstrap Test	Test Statistic	Asymptotic p-value	Bootstrap p-value
$lnCO_2$=f(lnGDP, lnREN, lnTO)	3.565	0.000	0.491

According to both the AMG and CCEMG estimation results, the variables lnGDP, lnREN, and lnTRADE have positive, negative, and positive effects on $lnCO_2$, respectively. Based on the AMG test results, a 1% increase in lnGDP leads to an approximately 0.40% increase in $lnCO_2$ emissions. A 1% increase in lnREN results in an approximately 0.25% reduction in $lnCO_2$ emissions, while a 1% increase in lnTRADE causes an approximately 0.06% increase in $lnCO_2$ emissions. Similar findings were obtained from the CCEMG estimation. According to the CCEMG test results, a 1% increase in lnGDP increases $lnCO_2$ by approximately 0.54%, a 1% increase in lnREN reduces $lnCO_2$ by approximately 0.26%, and a 1% increase in lnTRADE increases $lnCO_2$ by approximately 0.06%.

Table 8

AMG and CCE test results

Dependent variable: $lnCO_2$				
	AMG		**CCE**	
Independent variables	**Coefficient**	**Std. Error**	**Coefficient**	**Std. Error**
lnGDP	0.398***	0.147	0.541**	0.257
lnREN	−0.245***	0.021	−0.255***	0.041
lnTO	0.062*	0.032	0.059**	0.030
Constant	−5.280	3.464	−2.375	2.643

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

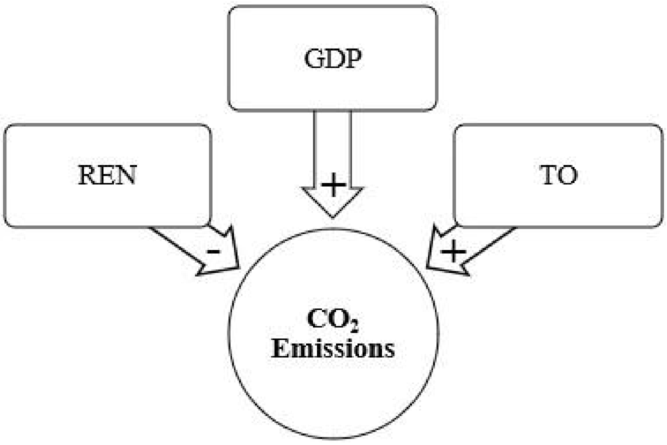
The results indicate that the study's key explanatory variable, TO, contributes to a slight increase in environmental degradation within OTS countries. These outcomes align with the research findings of Acaroğlu et al. (2023), Essandoh et al. (2020), Halicioglu (2009), Kalmaz & Kirikkaleli (2019), Le et al. (2016), and Wang et al. (2023), while they differ from the findings of Akın (2014), Al-Mulali et al. (2015), Dogan et al. (2017), Koc & Bulus (2020), Kohler (2013), and Shahbaz et al. (2013). Economic development levels significantly contribute to explaining these contrasting findings. In developing countries, the scale effect of trade generally dominates over the composition and technique effects. As countries become more developed, the demand for a cleaner environment increases, and environmental regulations and clean technologies are expected to become more prominent. In this context, the technique effect is expected to compensate for the scale effect in developed countries. Additionally, within the framework of the PHH, pollution-heavy industrial activities are prone to move from developed nations enforcing strict environmental policies to developing nations with weaker regulatory frameworks. Considering that the OTS countries examined in this study are classified as developing economies, the finding that TO contributes to environmental degradation is an expected outcome.

The increase in economic activity, similar to TO, also deteriorates the environmental quality. These findings align with the results of Acaroğlu et al. (2023), Bento & Moutinho (2016), Bilgili et al. (2016), Bölük

& Mert (2015), Du et al. (2022), Pata et al. (2023), and Shahbaz et al. (2013), yet contrast with those of Ali & Kirikkaleli (2022), Dogan et al. (2017), Hossain (2011), and Mirziyoyeva & Salahodjaev (2022). The income level and production structure may explain this divergence. eveloped countries engage in knowledge-intensive economic activities, whereas developing countries generally rely on pollution-intensive production methods. This leads to intensive fossil fuel use in developing countries. In countries that have not yet completed their structural transformation, economic activities are more likely to increase environmental pollution. As income levels rise, the production structure may gradually shift towards clean technologies. Considering the heavy reliance on fossil energy in the OTS countries, the negative environmental consequences of EG are expected. These findings largely align with both the EKC and the PHH. The OTS countries examined in this study are classified as developing economies and, in this regard, do not yet appear to have reached the turning point stage. Besides, the effect of REN on pollution was found to be negative and consistent with expectations. This result indicates that renewable energy improves the environmental quality, regardless of the countries' development levels or specific time periods. This finding has been supported by numerous empirical studies, including Acaroğlu et al. (2023), Ali & Kirikkaleli (2022), Ashraf et al. (2023), Bento & Moutinho (2016), Bilgili et al. (2016), Bölük & Mert (2015), Jeon (2022), Koc & Bulus (2020), Pata et al. (2023), and Xuan (2025). In this context, the relationship between renewable energy, environmental quality, and energy transition has become increasingly prominent. Figure 3 illustrates the direction and nature of the relationship between GDP, REN, TO, and CO_2 emissions.

Figure 3

Relationship among variables



Conclusion

This study investigates the link between trade openness and environmental degradation in the context of the OTS member countries. The empirical findings indicate that economic growth contributes to increased CO_2 emissions in these countries. Since the OTS countries are classified as developing economies, the observed rise in pollution levels aligns with the early stages of the EKC hypothesis, which states that increased environmental degradation usually follows economic growth. On the other hand, the results show that renewable energy consumption reduces CO_2 emissions, underscoring the environmentally friendly nature of these energy sources, which are associated with clean and modern technologies. The study's main explanatory variable, trade openness, was also found to worsen environmental pollution in the OTS countries. These results indicate that the scale effect of trade dominates its composition and technique effects in the member countries. Furthermore, the findings are consistent with the PHH.

Considering that the OTS countries are developing economies that rely heavily on fossil fuels for their final energy consumption, redirecting current financial resources towards environmentally friendly technologies is crucial for improving environmental quality. It is essential that these countries design compensatory policies to mitigate the adverse environmental impacts of trade and economic activity. The focus should be on increasing investment in renewable energy, enforcing more stringent and effective environmental regulations, and embracing industrial and trade policies that encourage economic activities to align with environmental sustainability. For OTS countries aiming to achieve the Sustainable Development Goals, strengthening environmental, trade and economic cooperation, supported by strong institutions and political commitment, should be a strategic priority.

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