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Air Freight Transport and Environmental Degradation: An Environmental Kuznets Curve Perspective

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Abstract

The expansion of the air transportation sector, which offers significant advantages in terms of time efficiency and spatial accessibility, plays a critical role in promoting economic growth. In turn, in economies experiencing sustained growth, the demand for air transportation also tends to rise. This reciprocal relationship between economic growth and air transport has important implications for environmental sustainability. This study examines the impact of air freight transportation on environmental degradation within the framework of the Environmental Kuznets Curve, using panel data from the ten countries with the highest number of airports over the period 2001–2020. In the study, the CIPS unit root test, the slope homogeneity test, and the panel cointegration test are applied sequentially. Subsequently, the PMG-ARDL approach is employed to estimate the short- and long-run relationship among the variables. Finally, the direction of causality between the variables is determined using the Dumitrescu–Hurlin panel causality test. The analysis also incorporates key determinants of environmental degradation, including trade openness, industrialization, income, renewable energy consumption, and technological advancement. The empirical results indicate that air freight transportation exacerbates environmental degradation. The results support the Environmental Kuznets Curve hypothesis and indicate that renewable energy use and industrialization contribute to environmental improvement, whereas trade openness tends to intensify environmental degradation. Additionally, a bidirectional causal relationship is found between air freight transportation and environmental degradation. Based on these findings, the study proposes policy recommendations aimed at mitigating environmental harm and promoting sustainable development.

Keywords: air freight transport; industrialization; renewable energy; trade openness; technology; Environmental Kuznets Curve; environmental degradation

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1. Introduction

Global warming and climate change have become critical global challenges, primarily driven by the surge in greenhouse gas (GHG) emissions resulting from the extensive use of fossil fuels since the onset of the Industrial Revolution (Lineman et al., 2015). The growth of international trade, industrial development, and economic growth has further intensified energy consumption, thereby increasing emissions released into the atmosphere through the burning of fossil fuels (Weber et al., 2021). Among the sectors contributing to this trend, transportation has emerged as a major source of GHG emissions and a key driver of climate

change. According to the International Energy Agency (IEA, 2023), air transportation is the second-fastest-growing source of emissions after road transport and currently accounts for approximately 2% of global energy-related carbon emissions.

Air transportation is a central part of the transportation of both goods and people, facilitating their movement from one place to another. The relationship between transportation and economic growth is inherently bidirectional, as demonstrated in various empirical studies (Baltaci et al., 2015; Brida et al., 2018; Hakim & Merkert, 2016; F. Zhang & Graham, 2020). The expansion of air transportation infrastructure and the increased movement of goods and services are generally expected to stimulate economic growth (Anwar et al., 2020). In turn, economic growth tends to support the further development of aviation infrastructure and the sustainability of air transport operations (Arvin et al., 2015). However, despite the positive role of transportation in promoting economic progress, it also contributes to a growing reliance on non-renewable energy sources to meet rising energy demands (Shafique et al., 2021). In this context, it is important to address the air pollution associated with economic growth and development to ensure sustainability and reduce pressure on the environment. Turning to energy-efficient green technologies in the transportation sector is important for ensuring sustainable growth (Shafique et al., 2020).

Air freight transport supports economic growth through the promotion of international trade expansion (Chatti, 2021). Trade openness helps the world economy grow through the increase in the volume of trade and income of all countries (Ghaderi et al., 2023; Q. Wang & Zhang, 2021). International trade produces GHG emissions because of the transportation of traded goods between trading partners (Cristea et al., 2013). The increase in trade volume from trade liberalization increases the demand for transportation (Hummels, 2009). According to the December 2023 report of the International Air Transport Association (IATA, 2023), the air cargo market is growing despite the slowdown in global trade and the rise in jet fuel prices. Cristea et al. (2013) found in their study that international transport emissions increased faster than trade due to distance and the expansion of air cargo transport.

One of the factors related to air transport is industrialization. The development of the transport sector increases a country's industrial value added by generating social and economic development (K. Ahmed et al., 2021). Industrialization generally contributes to environmental degradation through increased fuel consumption, the generation of substantial chemical waste, and the release of tiny, often invisible metallic and mechanical particles into the air (Voumik & Sultana, 2022). The evolution of air transportation, coupled with the expansion of economic activities in the area and rising energy requirements spurred by economic growth, is prompting nations to formulate ways of satisfying their energy demands. To this end, renewable sources of energy are assuming an increasing significance. Renewable energies have the potential to decrease nations' reliance on imported fossil fuels, enhance energy security, as well as minimize environmental degradation through the utilization of clean energies (Al-Mulali et al., 2016; Fatima et al., 2020).

With the growth of air transportation and the intensification of economic activities in the region, the amount of emissions released into the air is increasing. The important objective is to ensure sustainable growth by reducing emissions (H. Wang et al., 2021). Chandran and Tang (2013) highlighted several determinants of environmental degradation in their study, identifying economic growth and energy consumption as the most influential factors. Within the context of the Environmental Kuznets Curve (EKC), the relationship between income levels and environmental pollution has been extensively examined (Bahadır, 2022). This nexus was first investigated by Grossman and Krueger (1991), who laid the foundation for understanding the dynamic interplay between economic development and environmental outcomes. The EKC hypothesis posits an inverted U-shaped relationship,

suggesting that environmental degradation initially intensifies with economic growth but begins to decline after reaching a certain income threshold (Kearsley & Riddel, 2010). As the incomes of most nations keep on rising, there is a corresponding rise in environmental pollution in the form of higher emissions. The relationship between income and pollution has been examined in numerous studies, with findings varying across countries, time periods, and methodological approaches. However, the results found are similar to the recommendations in Grossman's research. Grossman (1995) emphasized that higher levels of economic growth can be achieved while avoiding a decline in the quality of life of future generations through the use of cleaner and more resource-efficient technologies.

Economic growth often stimulates increased transportation activities, infrastructure development, manufacturing output, and service sector expansion. However, the combined effects of economic growth, urbanization, industrialization, and the expansion of transport systems exert significant pressure on the environment (Arvin et al., 2015). While improvements in transportation infrastructure, growth in international trade, industrial expansion, and rapid technological development can drive national economic performance, they may simultaneously contribute to environmental degradation. These interconnected factors collectively intensify ecological stress. Grounded in this perspective, the primary objective of the present study is to analyze the impact of air transportation on environmental degradation within the framework of the EKC, while accounting for the roles of technological advancement, trade openness, industrialization, and renewable energy consumption. This research offers two key contributions to the literature. First, although prior studies have addressed the environmental consequences of air freight transportation, to the best of our knowledge, no existing research integrates industrialization, trade openness, technology, and renewable energy into a unified EKC framework focused on air transport. Second, the study uniquely considers a sample of countries with the highest number of airports, providing a targeted and policy-relevant perspective. Finally, the primary reason for focusing on air transport in this study is that air freight enables the rapid and reliable transportation of high-value, time-sensitive, and perishable goods, while its importance in global trade continues to grow. Indeed, the IATA (2025) report, based on 2024 data, indicates that increasing demand for rapid delivery and developments in maritime transport costs have enhanced the competitiveness of air cargo transport.

The remainder of the paper is organized as follows: Section 2 offers a comprehensive review of the related literature; Section 3 describes the data and methodological approach; Section 4 presents the empirical findings and related discussion; and finally, Section 5 concludes with key policy implications.

2. Literature Review

2.1. Nexus Between Freight and CO_2 Emissions

A substantial body of theoretical and empirical research has examined the interaction between air transport and economic growth (Chang & Chang, 2009; Button & Yuan, 2013; Hakim & Merkert, 2016; Brida et al., 2018; Alıcı & Akar, 2020; Balsalobre-Lorente et al., 2021; Ali et al., 2023). The interconnectedness of air transportation, economic growth, and environmental degradation has received considerable attention in recent years (S. Saidi & Hammami, 2017; Onifade et al., 2022).

Arvin et al. (2015) found a unidirectional causal relationship between air freight transport and CO_2 emissions in developed G20 countries over the period 1961–2012. Saleem et al. (2018) found a positive effect of air freight on GHG emissions in their study of the Next-11 countries over the period 1975–2015 and demonstrated the validity of the inverted U-shaped Kuznets Curve. Shafique et al. (2020) investigated the impacts of CO_2 emissions, economic prosperity, energy production, and urbanization on freight

transportation in terms of causality, and a one-way causality relationship was found from freight transport to CO_2 emissions in Hong Kong and Singapore, and from CO_2 emissions to freight transport in South Korea. Shafique et al. (2021) revealed that air freight transport has a positive contribution towards GHG emissions, with one-way causality from air freight to GHG emissions for the top 10 Asian economies with the highest CO_2 emissions during the period from 1995 to 2017. Habib et al. (2022) examined the connection between air transport intensity, air passenger travel, and air freight services and air transport-based CO_2 emissions for G20 nations for the period 1990–2016 and found a positive connection with carbon emissions. W. Wang et al. (2023) found that positive shocks in air cargo transportation, the insurance industry, and green investment result in reductions in carbon emissions in the long run in China over the period 1975–2020. Although the literature reports some context-dependent findings, the predominant evidence reviewed above indicates that air freight activity can increase emissions through greater fuel use and transport-related energy demand; accordingly, the theoretical expectation in this study is that air freight transportation has a positive impact on environmental degradation.

H_1. *Air freight transportation has a positive impact on environmental degradation.*

2.2. Nexus Between Trade Openness and CO_2 Emission

Trade has three effects on pollution: scale effect, technical effect, and composition effect (Antweiler et al., 2001). The scale effect is that the expansion of markets along with trade and the increase in production and consumption increase environmental degradation. The technical effect is argued to facilitate access to global markets and reduce environmental degradation through the development of more advanced production techniques, carbon-reducing technologies, and production processes (Nasir et al., 2021). It is argued that the effect of trade on pollution may be different according to the composition effect of the traded goods. It is argued that environmental degradation will increase as the share of environmentally harmful goods in national income increases (Copeland & Taylor, 2001). As international trade will increase with the expansion of the transportation network and industrialization, CO_2 emissions may also increase. Therefore, the impact of international trade on the environment is an issue that needs to be investigated.

When empirical research is reviewed, the impact of trade on emissions is mixed. Q. Wang and Zhang (2021) illustrate heterogeneous effects of trade openness on emissions depending on economic growth across 182 nations grouped by income level over the period 1990–2015. The paper found that higher trade openness reduces emissions in high-income and upper middle-income countries, but it does not significantly affect lower middle-income countries and actually raises emissions in low-income countries. Appiah et al. (2022) examined the impact of trade on carbon emissions in developing countries over the period 1971–2013 and found that imports, energy use, and industrialization increase carbon emissions. Pata et al. (2023) confirmed that the EKC is valid and found that real income and trade openness reduce environmental degradation in ASEAN countries. Ghaderi et al. (2023) analyzed the applicability of the EKC in the particular case of MENA countries between the years 1995 and 2018. The results show that both trade openness and energy consumption play an important role in increasing CO_2 emissions. Contrary to the above-mentioned studies, S. Zhang et al. (2017) found the validity of the EKC hypothesis and concluded that trade openness in the newly industrialized 10 selected countries between 1971 and 2013 increased trade in goods and services, especially technology transfer, and reduced carbon emissions by reducing capacity. Despite mixed empirical findings that reflect potentially opposing scale, technical, and composition effects of trade, this study's primary theoretical expectation is that the scale effect—through expanded production,

consumption, and transport activity—will dominate, leading to a positive relationship between trade openness and environmental degradation.

H_2. *Trade openness has a positive impact on environmental degradation.*

2.3. Nexus Between Industrialization and CO_2 Emission

Most studies on the relationship between industrialization and CO_2 emissions conclude that emissions increase due to industrialization. This is because the demand for energy, which increases as industrial activity increases with industrialization, is higher than in traditional agriculture and manufacturing (Sadorsky, 2013). Therefore, the literature generally suggests that a balance among economic growth, industrialization, and environmental sustainability should be achieved through the use of green resources (Mohsin et al., 2019).

U. Mentel et al. (2022) examined the relationship between industrial value added, renewable energy, and CO_2 emissions for 44 Sub-Saharan African countries between 1990 and 2015 under the EKC hypothesis and concluded that industrial value added has a positive impact on CO_2 emissions, that renewable electricity output decreases CO_2 emissions, and confirmed the EKC hypothesis. G. Mentel et al. (2022) concluded that industrial value added stimulates CO_2 emissions, renewable energy mitigates CO_2 emissions, and the EKC hypothesis is confirmed in 44 countries in Europe and Central Asia over the period 2000–2018. T. Li et al. (2019) examined the impact of industrialization on environmental quality in 31 regions of China for the period 2003–2017. An N-shaped relationship was confirmed between air pollution and industrialization. Sikder et al. (2022) for 23 developing countries, Voumik and Sultana (2022) for BRICS countries, Mahmood et al. (2020) for Saudi Arabia, Azam et al. (2022) for OPEC countries, and Ahmad et al. (2013) for SAARC countries found a positive impact of industrialization on CO_2 emissions.

Among studies related to the transportation sector, Guo and Meng (2019) investigated the driving factors of carbon dioxide emissions resulting from the transportation sector in the Beijing-Tianjin-Hebei region of China between 1995 and 2016. The study concluded that industrialization has different effects in different threshold regions. In low industrialization regions, the industrialization rate has a small impact on CO_2 emissions. In countries with high GDP, industrialization has also been found to have less impact on emissions. It has been stated that the impact of industrialization on emissions will decrease in the following stages and will become a factor that reduces CO_2 emissions originating from the transportation sector. Anwar et al. (2020) found that industrial value added per capita and transport freight have a negative impact on CO_2 emissions across 33 Belt and Road Initiative countries over the period 1986–2017 in the long run.

Unlike these studies, Claire and Widyawati (2023) examined the moderating effect of renewable energy on the relationship between industrialization and CO_2 emissions for the period 1990–2019 for ASEAN countries and concluded that while industrialization and economic growth boost CO_2 emissions, renewable energy mitigates CO_2 emissions as a result of its interaction with industrialization. However, the EKC hypothesis was confirmed to exist in the short term. While the environmental consequences of industrialization may differ across countries and development stages, the theoretical expectation in this study is that industrial expansion will increase energy demand and emissions, implying a positive relationship between industrialization and environmental degradation.

H_3. *Industrialization has a positive impact on environmental degradation.*

2.4. Nexus Between Renewable Energy and CO_2 Emission

The common conclusion of studies on renewable energy sources, which have become increasingly important in recent years, is that they reduce air pollution. Due to its significant contribution to climate change, renewable energy has become one of the most studied topics

by many researchers in recent years (Jiang et al., 2023). Increasing investment in renewable energy sources reduces fossil fuel use and reduces CO_2 emissions. Developing cost-effective renewable energy sources is becoming more important day by day (Raza et al., 2022). In studies applying panel data analysis, the same results are generally found regarding the impact of renewable energy on emissions. For example, Raza et al. (2022) found that the EKC was valid in the long term in South Asia between 1995 and 2018 and that renewable energy and the square of economic growth reduce emissions. Similar results were obtained by Hanif et al. (2022) for the ASEAN countries over the period 1995–2020. In the study, they confirmed the validity of EKC and concluded that renewable energy reduces emissions. Fatima et al. (2020) examined the effects of income, renewable energy, and non-renewable energy on CO_2 emissions under the EKC hypothesis in leading emitting countries over the period 1980–2014 and concluded that an increase in income reduces CO_2 emissions, while renewable energy also contributes to reducing emissions. Murshed (2024) analyzed the impact of the transition to renewable energy on emissions within the framework of EKC and concluded that there is an inverted U relationship between renewable energy and CO_2 emissions covering the period 2001–2021. Aydin et al. (2023) concluded that renewable energy reduces environmental degradation and improves environmental quality in Italy, Japan, the United Kingdom, and the United States between 1990 and 2018, while the EKC was confirmed only for the United States.

Chen et al. (2023) found that renewable energy has a negative impact on environmental degradation, whereas non-renewable energy has a positive impact on CO_2 emissions in China from 1990 to 2022. Deka et al. (2023a) concluded that renewable energy reduces CO_2 emissions in the European Union region between 1990 and 2019. Boudiaf (2023) found that renewable energy has a strong effect in the long term and a weaker effect in the short term in reducing carbon emissions in EU countries. Deka et al. (2023b) concluded that renewable energy negatively affects carbon emissions and therefore should be encouraged for Sub-Saharan African countries from 1990 to 2020. K. Saidi and Omri (2020b) found no causal relationship between renewable energy and CO_2 emissions in the long run but found bidirectional causality in the short run in 15 major renewable energy-consuming countries from 1990 to 2014. In their other studies examining OECD countries, K. Saidi and Omri (2020a) found different results for renewable energy in countries. They concluded that renewable energy reduces CO_2 emissions in the United States, Japan, Canada, Belgium, Germany, France, the United Kingdom, Sweden, Finland, Switzerland, and the Czech Republic, whereas it increases CO_2 emissions in South Korea and the Netherlands between 1990 and 2018. Given the reviewed evidence that renewable energy can displace fossil-fuel use and reduce emissions, the theoretical expectation in this study is that greater renewable energy consumption will have a negative impact on environmental degradation.

H_4. *Renewable energy has a negative impact on environmental degradation.*

2.5. Nexus Between Technology and CO_2 Emission

Literature studies have found both reducing and increasing effects of technological innovations on environmental degradation (Adebayo et al., 2023; Kartal & Pata, 2023). Technological innovation can help reduce environmental degradation through developments that increase energy efficiency and lower energy consumption (Adebayo et al., 2023). Adebayo et al. (2023) investigated BRICS countries for the period 1990–2019 using the CS-ARDL approach and found that technological innovations reduce emissions in both the short and long term. R. Wang et al. (2023) examined 14 EU countries using AMG and CCEMG methods for the period 1995–2020 and concluded that renewable energy and technological innovations reduce environmental pressure. Hordofa et al. (2023) examined China over the period from 1990 to 2020 using the ARDL method and found that environ-

mental innovation has a significant impact on limiting CO_2 emissions and a mitigating effect. Abid et al. (2022), in their study using the FMOLS method, found that technological innovation has a reducing impact on CO_2 emissions in G8 countries between 1990 and 2019. Safi et al. (2021) applied the CS-ARDL and CCEMG estimators for G7 countries between 1990 and 2019 and found that environmental R&D has a decreasing effect on carbon emissions.

On the other hand, some studies have found a positive impact on CO_2 emissions. This may be due to the lack of investment in green technologies, despite technological innovation in countries (Adebayo & Kirikkaleli, 2021). Kartal and Pata (2023) indicated that technological innovation has different effects on CO_2 emissions. In their study, technological innovation has an increasing effect on CO_2 emissions at higher quantiles. Although some studies identify emission-increasing or mixed effects of technological innovation, particularly where innovation is not directed toward environmental objectives or its effects vary over time, the theoretical expectation in this study emphasizes the potential of technological progress to improve energy efficiency and reduce energy consumption; therefore, a negative relationship with environmental degradation is hypothesized.

H_5. *Technological innovation has a negative impact on environmental degradation.*

3. Data, Model and Methodology

3.1. Data and Model

The present research explores how air freight activity, trade liberalization, industrial growth, renewable energy deployment, and technological progress influence CO_2 emissions under the framework of the EKC hypothesis. For this purpose, panel data techniques are applied to a sample of countries hosting the largest number of airports, covering the years 2001–2020. The variables are expressed in logarithmic form, with data drawn from the World Bank's World Development Indicators and the BP Statistical Review of World Energy. The sample period was determined by the availability of data for the countries and variables included in the analysis, with 2020 being the final year for which the required data were available. However, 2020 coincided with the COVID-19 pandemic, which caused exceptional disruptions to economic activity and air transportation. These disruptions may have influenced the estimated relationships, particularly those involving air freight transportation and CO_2 emissions. Since the analysis does not separately isolate the pandemic-related shock or exclude 2020, its potential effect cannot be identified independently. Accordingly, the results should be interpreted as reflecting the relationships over the full 2001–2020 sample period, including the exceptional conditions in the final year. The model is given below:

$$CO_2 = f\,(GDP, GDPS, FREIGHT, TRADE, IND, REN, TECH) \quad (1)$$

The variables, abbreviations, units of measurement, and data sources are listed in Table 1. The econometric model is formulated as follows:

$$\begin{aligned} lnCO_{2\ i,t} = {} & \alpha_0 + \alpha_1 lnGDP_{\ i,t} + \alpha_2 lnGDP^2_{\ i,t} + \alpha_3 lnFREIGHT_{\ i,t} + \\ & \alpha_4 lnTRADE_{\ i,t} + \alpha_5 lnIND_{\ i,t} + \alpha_6 lnREN_{\ i,t} + \alpha_7 lnTECH_{\ i,t} + \varepsilon_{i,t} \end{aligned} \quad (2)$$

$$i = 1, 2, \ldots\ldots 10;\ t = 2001 \ldots 2020.$$

i = 1 = United States, i = 2 = Russian Federation, i = 3 = Mexico, i = 4 = South Africa i = 5 = Colombia, i = 6 = Canada, i = 7 = Brazil, i = 8 = Argentina, i = 9 = Bolivia, i = 10 = Indonesia.

The number of airports is used as the primary criterion for selecting the countries. Based on 2019 data published by the Geo Factbook (2026) database, the top 11 countries

worldwide with the highest number of airports were initially considered for inclusion in the sample. According to the same ranking, China and Japan were placed 14th and 33rd, respectively, and therefore did not meet the top-11 selection criterion. However, Paraguay was excluded from the analysis due to the unavailability of data for the relevant variables. Consequently, the final sample consists of the remaining 10 countries.

In the equation, α_1, α_2, α_3, $\alpha_4, \alpha_5, \alpha_6, \alpha_7$, represents the coefficients to be estimated; $\varepsilon_{i,t}$ is the error term. In the context of the EKC, the expected coefficient sign for GDP (α_1) is positive, whereas that for GDP^2 (α_2) is negative. In line with the hypotheses formulated based on the theoretical arguments and empirical literature reviewed in the previous section, the expected coefficients of air freight transportation (FREIGHT), trade openness (TRADE), and industrialization (IND) are positive. These expectations reflect the potential for increased freight activity, trade-related expansion in production and consumption, and industrial energy demand to contribute to higher CO_2 emissions. By contrast, the expected coefficients of renewable energy (REN) and technological innovation (TECH) are negative, as these factors are expected to support emission reduction. The expected signs are empirically examined using the PMG-ARDL framework, which allows the effects to be distinguished between the long run and the short run.

Table 1. Definitions of variables.

Variables	Abbreviations	Unit of Measurement	Sources
CO_2 Emissions	lnCO_2	Metric tons per capita	Energy Institute (2023)
Gross Domestic Product	lnGDP	Per capita in constant 2015$	World Bank (2023)
Air Freight Transportation	lnFREIGHT	Air freight is the volume of freight, express, and diplomatic bags carried on each flight stage (million ton-km)	World Bank (2023)
Trade Openness	lnTRADE	Imports + exports as a percentage of GDP (%)	World Bank (2023)
Industrial Value Added	lnIND	Constant 2015 US$	World Bank (2023)
Technology	lnTECH	Research and development expenditure as a percentage of GDP (%)	World Bank (2023)
Renewable Energy	lnREN	Renewable energy consumption to final energy consumption (%)	World Bank (2023)

3.2. Methodology

To begin with, cross-sectional dependence (CSD) and slope homogeneity tests are carried out to determine whether the countries in the panel are interrelated. Subsequently, the CIPS unit root test, categorized as a second-generation test, is employed to evaluate the stationarity of the series. Since cross-sectional dependence is detected across the countries, the CIPS approach is preferred. In the following step, the analysis investigates whether a long-run cointegration association exists among the variables. At the fourth stage, the panel PMG-ARDL framework is implemented to estimate the influence of the explanatory factors on CO_2 emissions. Lastly, the Dumitrescu–Hurlin causality approach is applied to identify the causal direction among the variables.

3.2.1. CSD and Slope Homogeneity Test

The CSD and slope homogeneity tests guide us on which unit root and cointegration test to proceed with in the econometric analysis. Macroeconomic time series from different countries may be affected by the same event, leading to dependencies between countries in the panel (Munir et al., 2020). Estimates obtained without conducting a cross-sectional dependence test may be biased and inconsistent (Pesaran, 2007). In the study, we applied the Breusch and Pagan (1980) LM test, the Pesaran (2004) scaled LM test, and the bias-adjusted LM test proposed by Pesaran et al. (2008).

The null hypothesis (H_0) of no CSD is tested against the alternative hypothesis (H_1) of the existence of CSD.

The slope homogeneity test proposed by Pesaran and Yamagata (2008) is an improvement of the Swamy (1970) test. The Swamy test statistic, which follows an asymptotically normal distribution, includes the $\underline{\Delta}$ and $\underline{\Delta}_{adj}$ statistics for testing the homogeneity of the slope coefficients.

Under the null hypothesis H_0: $\beta_i = \beta$ (for all i), the slope coefficients are homogeneous, against the alternative hypothesis H_1: $\beta_i \neq \beta_j$ (for a non-zero fraction of pairwise slopes for i ≠ j) (Pesaran & Yamagata, 2008). The homogeneity assumption for the estimated parameters, which is defined as the null hypothesis, is not able to capture country-specific characteristics, whereas the alternative hypothesis accounts for country-specific characteristics in panel data (Nazlıoğlu et al., 2011).

3.2.2. Panel Unit Root Test

Based on the findings of the CSD and slope homogeneity analyses, the study employs the Cross-sectionally Augmented Dickey–Fuller (CADF) and the Cross-sectionally Im–Pesaran–Shin (CIPS) statistics. These second-generation unit root tests are designed to account for cross-sectional dependence in the data.

The CADF procedure extends the conventional ADF regression by incorporating lagged levels, cross-sectional means, and the first-order differences in the individual series. This framework yields novel asymptotic properties, both for the individual CADF statistics and for their arithmetic averages.

The CADF test statistic is computed through the following regression model:

$$\Delta y_{it} = \alpha_i + b_i y_{i,t-1} + c_i \underline{y}_{t-1} + d_i \Delta \underline{y}_t + \epsilon_{it} \quad (3)$$

$$\text{i} = 1, 2\ldots, \text{N} \qquad \text{t} = 1, 2\ldots \text{T}$$

In this formulation, the difference operator is denoted by Δ, the individual constant is represented by α_i and b_i together with c_i refer to the fixed-effect coefficients. The symbol ϵ_{it} is assigned to the error term specific to each cross-section, while $y_{i,t}$ stands for the initial observations assumed to follow a density function with measurable mean and variance.

$$\Delta y_i = (\Delta y_{i1}, \Delta y_{i2}, \ldots \Delta y_{iT})', \; y_{i-1} = (y_{i0}, y_{i1}, \ldots y_{i,t-1}) \quad (4)$$

The standard formulation of the CIPS measure is computed as the mean of the individual $CADF_i$ statistics. The testing framework posits, under H_0, that the series is non-stationary due to a unit root, while H_1 contends that stationarity holds for at least one cross-sectional dimension.

3.2.3. Durbin-Hausman Cointegration Test

An important strength of the Durbin–Hausman test is its applicability irrespective of whether the explanatory variables are integrated of order zero, I(0), or order one, I(1). There

are two statistics, referred to as the Durbin–Hausman group statistics, depending on the homogeneous or heterogeneous structure of the panel. The testing framework defines H_0 as the scenario where the variables are not cointegrated, in contrast to H_1, which indicates the existence of a long-run cointegration association.

3.2.4. Panel PMG-ARDL Technique

The Panel Autoregressive Distributed Lag (ARDL) approach, introduced by Pesaran et al. (1999), is used to model both short-run and long-run relationships between the variables in a heterogeneous panel data context. The Pooled Mean Group (PMG) estimator is particularly useful because it allows for short-run coefficients, error variances, and adjustment dynamics to be heterogeneous across cross-sectional units but imposes homogeneity in the long-run coefficients. The flexibility of the PMG-ARDL method is particularly appropriate for empirical investigation of countries or firms that are likely to have heterogeneity in their short-run adjustments to shocks but are assumed to have a common long-run equilibrium relationship.

Additionally, the PMG estimator can accommodate regressors with a mixed order of integration, specifically I(0) and I(1), provided that the variables do not exhibit integration of order two or higher. The error correction specification incorporated within the ARDL model further guarantees consistency and efficiency by effectively modeling equilibrium adjustments along with short-run dynamics (Pesaran et al., 1999). This methodological approach is anticipated to yield robust estimates, especially in settings characterized by cross-sectional heterogeneity and potential endogeneity.

As a supplementary diagnostic, variance inflation factors (VIFs) were calculated to assess potential multicollinearity among the explanatory variables. The VIF values ranged from 1.33 to 8.25, remaining below the commonly used threshold of 10. These results do not indicate severe multicollinearity among the explanatory variables.

3.2.5. Panel Causality Test

Dumitrescu and Hurlin's (2012) methodology extends the traditional Granger (1969) causality test to heterogeneous panel data contexts, allowing for the presence of fixed coefficients across cross-sectional units. The causality test, which is an improved version of the Granger causality test, has many advantages such as taking CSD into account, being usable in cases where T > N or N > T, and being applicable in unbalanced panel data models (Dumitrescu & Hurlin, 2012).

The linear model created in this direction is as follows:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \beta i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \quad (5)$$

α_i, represents the constant parameter in the time dimension. "K" represents the lag length and is assumed to be the same for all cross-sectional units of the panel in the balanced panel. $\gamma i^{(k)}$, lagged parameters, $\beta i = \beta i^{(1)}, \beta i^{(2)} \ldots\ldots \beta i^{(K)}$, "$\gamma i^{(k)}$", autoregressive parameters, "$\beta i^{(k)}$", the slope of the regression coefficients differs between the groups.

The null and alternative hypotheses created to determine the Dumitrescu-Hurlin causality relationship are as follows (Lopez & Weber, 2017):

$$H_0: \ \beta_{i1} \ldots \beta_{ik} = 0 \quad \forall_{i1} = 1, \ \ldots N$$

$$H_1: \ \beta_{i1} \ldots \beta_{ik} = 0 \quad \forall_{i1} = 1, \ \ldots N_1$$

$$\beta_{i1} \neq 0 \text{ or } \beta_{ik} \neq 0 \quad \forall_{i1} = N_1 + 1 \ldots, \ N$$

H_0: There is no causal relationship for all units in the panel.

H_1: There is a causal relationship for some units in the panel.

4. Findings and Discussion

The first stage of the analysis involves descriptive statistics. Table 2 presents descriptive statistics including minimum, maximum, median, mean, standard deviation, skewness, and kurtosis.

Table 2. Descriptive statistics.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
$lnCO_2$	0.754144	0.731491	1.304739	0.133288	0.377823	−0.158748	1.642759
lnGDP	4.091496	3.963778	4.783174	3.602877	0.360910	0.826411	2.182568
lnGDPS	16.86978	15.71154	22.87876	12.98072	3.062008	0.888048	2.230380
lnFREIGHT	3.178037	3.113435	4.633320	1.883221	0.658077	0.730792	3.438138
lnTRADE	1.621959	1.640032	1.906116	1.339496	0.159482	−0.102934	1.741667
lnIND	11.43283	11.50827	12.56876	10.67014	0.503989	0.808905	3.187749
lnREN	1.103993	1.006037	1.699404	0.502427	0.345231	0.058028	2.08174
lnTECH	−0.09133	−0.05501	0.534390	−0.876475	0.345335	−0.177767	2.222906

In the descriptive statistics, the highest mean value is observed for the lnGDP variable, while the lowest mean value is observed for the lnTECH variable. Among the maximum values, lnIND has the highest value, whereas lnTECH has the lowest.

The results of the CSD and slope homogeneity tests are presented in Table 3. The test statistics indicate significant values for all variables, meaning that the null hypothesis is strongly rejected at the 1% significance level. It can be concluded that a shock in one country influences the other countries. In other words, the variables are simultaneously affected by common shocks. The null hypothesis of slope homogeneity is also rejected at the 1% significance level, confirming the alternative hypothesis. The slope coefficients are heterogeneous. At this stage of the econometric analysis, the CADF and CIPS unit root tests, which account for CSD and slope homogeneity, are performed. Table 4 presents the results of the unit root tests.

Table 3. CSD and slope homogeneity test results.

Variables	Breusch Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM
$lnCO_2$	140.2342 *	13.92888 *	13.71836 *
lnGDP	414.7845 *	50.61721 *	50.40669 *
lnGDPS	414.0261 *	50.51586 *	50.30533 *
lnFREIGHT	143.9372 *	14.42371 *	14.21318 *
lnTECH	146.3201 *	14.74214 *	14.53162 *
lnIND	362.6494 *	43.65036 *	43.43983 *
lnTRADE	108.2063 *	9.648970 *	9.438444 *
lnREN	92.97638 *	7.613790 *	7.403263 *
	statistics	***p*-value**	
Delta	5.970 *	0.0000	
Adj. Delta	8.050 *	0.0000	

Note: * denotes significance at the 1% level. The values reported for the CD test represent test statistics.

Table 4. Panel unit root test results.

Variables	At Level, Constant	At First Difference, Constant	CADF I(0)	CADF I(1)
$lnCO_2$	−2.249	−4.126 *	−3.225	−6.256 *
lnGDP	−1.707	−2.903 *	−3.24	−5.913 *
lnFREIGHT	−2.715	−4.468 *	−3.326	−4.154 *
lnTECH	−2.552	−3.853 *	−2.552	−6.514 *
lnIND	−1.147	−2.845 **	−3.219	−4.625 *
lnTRADE	−2.118	−4.612 *	−2.666	−2.546 *
lnREN	−2.840	−4.322 *	−3.128	−4.649 *

Note: * and ** denote significance at 1% and 5% levels.

Based on the CIPS unit root test, none of the variables are stationary at level, indicating the presence of unit roots. The variables become stationary at the first difference. The existence of a cointegration relationship among variables in the long run is investigated using the Durbin-Hausman cointegration test. The results of the cointegration test are presented in Table 5.

Table 5. Durbin–Hausman cointegration test results.

Tests	Constant, Statistics	Prob.	Constant and Trend, Statistics	Prob.
DHpanel	−2.490 *	0.006	−2.517 *	0.006
DHgroup	−2.267 *	0.012	−2.324 *	0.010

Note: * denotes significance at the 1% level.

The null hypothesis is rejected at the 1% significance level for both the group and panel statistics, indicating the presence of cointegration among the variables in the long run. In other words, the variables are cointegrated under both the constant and constant-and-trend specifications. After performing these tests, we employ the PMG-ARDL technique for both long- and short-run analysis.

Table 6 shows that all variables are significant in the long run, and the results support the EKC hypothesis. Carbon emissions increase at lower income levels, whereas emissions decrease as income rises beyond a certain threshold. To identify this threshold more precisely, the turning point of the EKC is calculated using the estimated long-run coefficients of lnGDP and $lnGDP^2$. The turning point is obtained as 4.774 in logarithmic income terms, corresponding to approximately USD 59,442 per capita in constant 2015 prices. This value falls within the observed income range of the sample, indicating that the estimated inverted U-shaped relationship is economically plausible within the sample period. Thus, environmental degradation tends to increase with economic development up to approximately USD 59,442 per capita, after which further increases in income are associated with declining CO_2 emissions. Both short-run and long-run estimations show that renewable energy has a negative and statistically significant relationship with emissions. This result implies that renewable energy consumption helps reduce environmental pollution. The findings regarding renewable energy use indicate a negative effect on CO_2 emissions, as expected, and are consistent with the findings reported in the existing literature (Fatima et al., 2020; Raza et al., 2022; Aydin et al., 2023; Murshed, 2024). This result indicates that sustaining investments in renewable energy can contribute to enhancing environmental sustainability. Air freight has a positive impact on CO_2 emissions in both the short run and the long run; however, the short-run impact is statistically insignificant. The results are consistent with those of Shafique et al. (2021) and Habib et al. (2022). The impact of trade on emissions is

statistically significant in both the long and short term; however, the direction of this effect varies across time horizons. It has been demonstrated that while trade has an emission-increasing effect in the long run, it has an emission-reducing effect in the short run. The results show similarities to the studies by Lv and Xu (2019) and Q. Wang and Zhang (2021). Lv and Xu (2019) stated that the short-term emission-reducing effect of trade openness stems from access to cleaner technologies. However, the long-term increase in emissions stems from the expansion of economic activities triggered by higher trade volumes and the growing need for fossil fuels to meet rising energy demand. The technology variable was found to have a long-term mitigating effect on emissions, as expected; this result aligns with the findings of studies by Adebayo et al. (2023) and R. Wang et al. (2023).

Table 6. PMG-ARDL test results.

Variables	Long Run		Short Run	
	Statistics	***p*-Value**	**Statistics**	***p*-Value**
lngdp	8.918 (3.056)	0.0000 *	4.592 (25.30)	0.8564
lngdps	−0.934 (0.373)	0.0144 *	−0.818 (3.092)	0.7918
lnfreight	0.151 (0.041)	0.0000 *	0.014 (0.027)	0.6014
lnind	−1.737 (0.306)	0.0000 *	0.039 (0.179)	0.8268
lntrade	0.734 (0.174)	0.0000 **	−0.112 (0.056)	0.0487 **
lnren	−0.237 (0.088)	0.000 *	−0.387 (0.230)	0.0968 ***
lntech	−0.138 (0.073)	0.0000 *	−0.057 (0.056)	0.9191
Cointeq			−0.148 (0.059)	0.0139 *

Note: Standard errors are reported in parentheses. *, **, *** denotes significance at 1%, 5% and 10%.

Also, the impact of industrialization on CO_2 emissions is found to be statistically significant and negative. The findings regarding renewable energy use indicate a negative effect on CO_2 emissions, as expected, and are consistent with the findings reported in the existing literature (Fatima et al., 2020; Raza et al., 2022; Aydin et al., 2023; Murshed, 2024). This finding suggests that continued investment in renewable energy technologies could contribute to enhancing environmental sustainability. This empirical result is consistent with previous studies examining the long-run effects of industrialization on CO_2 emissions. For example, F. Ahmed et al. (2022) revealed that industrialization had a negative impact on CO_2 emissions in the long run for Asia–Pacific countries over the period 1995–2020 and confirmed the validity of the EKC hypothesis. Riaz et al. (2025) found that industrialization had a mitigating effect on emissions in NATO countries during the period from 1985 to 2019. However, in contrast, while the impact of industrialization on CO_2 emissions in the short term is positive, it appears to be statistically insignificant. This finding is consistent with studies by K. Li and Lin (2015), Pal et al. (2025), and Polat et al. (2026). K. Li and

Lin (2015) demonstrated that the effect of industrialization had an insignificant impact on CO_2 emissions in middle- and high-income countries over the period 1971–2020. Pal et al. (2025) demonstrated that industrialization had a positive but statistically insignificant long-run effect on emissions in Asian countries. Polat et al. (2026) found a positive but statistically insignificant impact on both ecological footprint and greenhouse gas emissions in sub-Saharan African countries. The hypotheses are evaluated based on the direction and statistical significance of the estimated long-run coefficients obtained from the PMG-ARDL model. Accordingly, Table 7 summarizes whether the long-run results support each of the five directional hypotheses l.

Table 7. Summary of hypothesis test results.

Hypothesis	Explanation	Results
H_1	Air freight transportation has a positive impact on environmental degradation.	Supported
H_2	Trade openness has a positive impact on environmental degradation.	Supported
H_3	Industrialization has a positive impact on environmental degradation.	Not supported
H_4	Renewable energy has a negative impact on environmental degradation.	Supported
H_5	Technological innovation has a negative impact on environmental degradation.	Supported

Table 8 presents the causality test results and reveals bidirectional causality between economic growth and carbon emissions. Bidirectional causality between industrialization, air freight, and emissions is also confirmed. The causal relationship running from CO_2 emissions to air cargo transport can be explained by improvements implemented within the air transport sector. Measures taken to alleviate the environmental pressure caused by high CO_2 emissions resulting from economic activities include actions targeting air cargo transport operations. Practices such as taxation, incentives and subsidies, the transition to sustainable aviation fuels, carbon pricing and offsetting mechanisms, and fleet modernization can be viewed as factors that indirectly affect and contribute to reducing environmental pressure. Moreover, the results are consistent with the evidence reported by Fatima et al. (2020) of bidirectional causality between trade openness, economic growth, and CO_2 emissions.

Table 8. Dumitrescu–Hurlin causality results.

Variables	W Stat	Z-Bar	*p*-Value
$\ln CO_2 > \ln GDP$	2.7066	3.4132	0.0006 *
$\ln GDP > \ln CO_2$	4.3470	6.6940	0.0000 *
$\ln CO_2 > \ln TECH$	3.0448	4.0896	0.0001 *
$\ln TECH > \ln CO_2$	3.8397	5.6794	0.0000 *
$\ln CO_2 > \ln REN$	1.0154	0.0308	0.9754
$\ln REN > \ln CO_2$	2.6273	3.2547	0.0011 *
$\ln CO_2 > \ln FREIGHT$	1.8407	1.6814	0.0927 ***
$\ln FREIGHT > \ln CO_2$	2.7502	3.5004	0.0005 *
$\ln CO_2 > \ln IND$	1.9598	1.9196	0.0549 ***
$\ln IND > \ln CO_2$	3.4806	4.9611	0.0000 *
$\ln CO_2 > \ln TRADE$	2.7698	3.5396	0.0004 *
$\ln TRADE > \ln CO_2$	2.9092	3.8185	0.0001 *

Note: * and *** denote significance at 1% and 10% levels.

A one-way causality is found running from renewable energy to carbon emissions. In order to reduce the GHG emissions generated by economic activities associated with air transportation infrastructure, greater emphasis should be placed on the use of, and investment in, renewable energy sources as alternative energy solutions.

5. Conclusions and Policy Recommendations

Within the context of the EKC hypothesis, this study explores the impact of air freight operations, trade openness, industrial growth, renewable energy implementation, and technology on CO_2 emissions. For this purpose, a panel dataset covering countries with the greatest number of airports over the period 2001–2020 was analyzed, based on the availability of relevant data through 2020.

Findings obtained from the PMG-ARDL procedure validate the EKC hypothesis. The analysis demonstrates that all investigated variables have significant long-run effects on CO_2 emissions. Over the long term, GDP, air freight, and trade openness increase emissions, whereas industrialization, renewable energy utilization, and technological progress are associated with reductions. Examination of short-term impacts indicates that trade openness and renewable energy mitigate CO_2 emissions, while the influence of other explanatory variables is statistically negligible. The positive effect of air freight on emissions highlights the environmental price of the development of global transport and logistics networks, which, while vital to economic connectivity, present considerable obstacles to attempts at reducing carbon output. Developing sustainable air transport policies to mitigate the long-run impact of air transport on CO_2 emissions is a matter of importance. In this context, compliance with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program is recommended to ensure regular monitoring, reporting, and verification (MRV) of CO_2 emissions from international aviation as well as to determine emission offsetting obligations. The implementation of this program can contribute to achieving global emission reduction targets and carbon-neutral growth goals. In line with the goal of achieving net-zero carbon emissions by 2050, it is crucial to promote Sustainable Aviation Fuel (SAF) as an alternative to fossil fuels for aviation, to establish and scale up the necessary mechanisms, and to foster technological innovations. Tax reductions and incentive mechanisms should be developed for air cargo companies that adopt alternative and sustainable aviation fuels. As part of fleet modernization, replacing older, less fuel-efficient aircraft with new-generation aircraft—featuring advanced engine technologies, high operational and energy efficiency, and lower emissions—can contribute to reducing emissions from air transport. The result that trade openness boosts CO_2 emissions in the long term but decreases them in the short term implies a complex nexus. It implies that higher trade integration promotes the transfer of cleaner technologies and boosts efficiency initially; however, in the long term, higher trade may result in higher production and transportation emissions. The fact that trade openness increases emissions in the long run necessitates aligning trade policies with environmental sustainability goals. The transition to technologies that enhance energy efficiency and the use of clean energy in the production of traded goods can be supported through tax breaks, incentives, and subsidies. To mitigate the environmental degradation resulting from the increased transport demand associated with rising trade volumes, low-carbon logistics and transportation practices must be widely adopted. Fostering collaborations that support green technology transfers and technological investments between countries can contribute to emission reductions.

The mitigation impact of industrialization on CO_2 emissions may stem from increased energy efficiency driven by technological advancements and a rising share of renewable energy sources in the production process. Another reason could be the shift from traditional, high-energy-demand sectors to technology-intensive sectors, resulting in lower

energy intensity and higher value-added generation. The Dumitrescu–Hurlin causality analysis further uncovers bidirectional causal linkages between economic growth and CO_2 emissions, industrialization and CO_2 emissions, technology and CO_2 emissions, air freight and CO_2 emissions, and trade and CO_2 emissions. Moreover, a unidirectional causal relationship running from renewable energy to CO_2 emissions is detected.

The findings of this study provide important insights into the environmental implications of economic activities, particularly for countries with extensive air transport networks. The confirmation of the EKC hypothesis indicates that, even if economic growth first leads to rising levels of CO_2 emissions, when a particular level of income is attained, additional growth leads to better quality of the environment. However, the adverse long-run effects of GDP, air freight, and trade openness on CO_2 emissions show that these countries continue to experience severe environmental pressures associated with economic development. Under a more optimistic scenario, industrialization, the deployment of renewable energy sources, and technological advancement have been found to contribute to a sustained decline in CO_2 emissions. Overall, these findings point to opportunities for an economic system that can simultaneously sustain growth and ensure environmental protection, provided that sufficient investment is made in clean technologies and sustainable industrial development.

From a theoretical perspective, the findings contribute to the Environmental Kuznets Curve (EKC) literature by demonstrating that the environmental implications of economic activity differ across its components and over time. Although the EKC hypothesis is supported, the positive long-run effects of GDP, air freight transportation, and trade openness indicate that economic expansion and greater integration into global markets may continue to exert pressure on the environment in countries with extensive airport infrastructure. At the same time, the negative long-run effects of industrialization, renewable energy consumption, and technological progress suggest that the relationship between economic development and environmental quality is not determined by growth alone but is also associated with the energy and production characteristics of that growth. The finding that trade openness increases emissions in the long run but reduces them in the short run further highlights the importance of distinguishing short-term adjustment effects from long-term relationships when examining the trade-environment nexus. Overall, these results extend the application of the EKC framework to air freight-intensive economies by considering transport activity alongside broader economic, energy, and technological factors.

Based on these findings, several policy recommendations can be made: Governments need to foster green industrial policies that encourage low-carbon technologies and sustainable production methods. Incentives for industries that adopt clean energy, resource efficiency, and pollution control measures are necessary. Incorporating carbon footprint measurements into trade agreements and promoting environmentally friendly imports and exports can help align trade openness with climate objectives. Investment in research and development can be prioritized to foster and disseminate low-carbon technologies across sectors. Policymakers can implement incentives and regulations to make the air freight industry more efficient. Promoting sustainable aviation fuels and enhancing logistics efficiency can minimize the environmental impact of air freight. Finally, since renewable energy exhibits a robust causal relationship with lower CO_2 emissions, governments should accelerate the transition to renewable energy through targeted subsidies and investment in community-based renewable energy projects.

The study period is limited to 2020 due to data availability. For future studies, the study period can be extended with available data. Future studies could examine developing countries with high rates of industrialization within the EKC framework. In addition to air transport, future studies could incorporate road and rail transport and examine their respective impacts on emissions separately.

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