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Relationship Between Economic Complexity, Globalization, Energy Sources and Environmental Sustainability

Mustafa Naimoğlu, **Mustafa Akal**

Mustafa Naimoğlu (*corresponding author,* e-mail: mnaimoglu@bingol.edu.tr), Bingöl University, Faculty of Economics and Administrative Sciences, Bingöl, Turkey

Mustafa Akal (e-mail: akal@sakarya.edu.tr), Sakarya University, Faculty of Political Sciences, Sakarya, Turkey

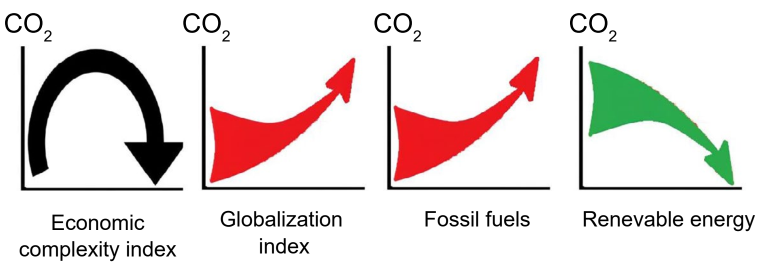
Abstract

This study investigates the relationship between economic complexity, globalization, energy consumption patterns and CO_2 emissions in 12 energy-importing emerging economies from 1996 to 2020. Employing panel data analysis, the autoregressive distributed lag (ARDL) model is utilized. The findings reveal a U-shaped relationship between economic complexity and air pollution, supporting the environmental Kuznets curve (EKC) theory. Renewable energy demonstrates a significant ability to reduce CO_2 emissions over the long term, while fossil fuel use exacerbates environmental degradation. Economic globalization is associated with increased CO_2 emissions, contradicting expectations. The short-term results align with the long-term findings, highlighting significant country-specific variations. The policy implications highlight the necessity of promoting renewable energy adoption and reducing reliance on fossil fuels. This research contributes to EKC literature by focusing on energy-importing economies, emphasizing the importance of multidimensional analyses in environmental policy formulation. The study underscores the critical role of renewable energy investment and carbon pricing strategies in mitigating environmental degradation while encouraging sustainable development pathways.

Keywords: Economic complexity, renewable energy, fossil energy, globalization, EKC hypothesis, energy-importing emerging economies

JEL Classification: Q43, Q56, O13, O44

Graphical abstract



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1. Introduction

During the early 1900s, global CO_2 emissions stood at approximately 2 billion tonnes. By 2018, this figure surged by approximately 1,600%, reaching 36.2 billion tonnes (Gurler *et al*., 2020). Consequently, environmental degradation has garnered considerable attention across various disciplines over the past century. The escalating demand, fuelled by population growth, exerts immense pressure on natural resources, which cannot sustainably meet these needs (Aydin *et al*., 2023). Moreover, the inefficient and excessive use of resources causes irreversible damage to the biosphere. (Subramanian *et al*., 2023; Xuan *et al*., 2023). Additionally, given the global reliance on energy imports, the preference for easily accessible fossil fuels devoid of complex technology exacerbates environmental harm, impeding sustainable energy and development goals.

The interplay between the ecosystem and the economy is crucial to understanding environmental challenges. (Kurchenkov *et al*., 2020; Barrett *et al*., 2022; Sharif *et al*., 2023). The excessive consumption of natural resources due to increasing industrialization poses a significant threat to global liveability, exemplified by the COVID-19 pandemic. This scenario underscores the urgency for a sustainable future (Adnan *et al*., 2022; Cox and White, 2023). As economic activities surge, so do CO_2 emissions, contributing to challenges such as climate change and biodiversity loss (Huang *et al*., 2022; Avotra and Nawaz, 2023). Moreover, the drive for heightened production and competitiveness, particularly in developing countries such as China and India, exacerbates environmental degradation.

Efforts to address these challenges have included international agreements such as the Montreal and Kyoto Protocols, and the Paris Agreement. Despite commitments to enhance air quality, factors such as production greed and economic competition have impeded the fulfilment of these commitments.

The nexus between economic development and environmental degradation has long intrigued scholars (Munasinghe, 1999). Research indicates an inverted U-shaped relationship between economic growth and environmental pollution (Grossman and Krueger, 1991; Zambrano-Monserrate *et al*., 2018; Khan *et al*., 2022; Shokoohi *et al*., 2022; Peng *et al*., 2023; Qi *et al*., 2023), suggesting that as economies develop, environmental degradation initially increases before declining after reaching a certain threshold.

Studies exploring the relationship between the ecosystem and the economy are burgeoning and becoming more comprehensive. Apart from investigating the impact of economic development on the environment, there is a focus on the link of the economic complexity index to the environment (Adedoyin *et al*., 2022; Balsalobre-Lorente *et al*., 2022; Mehrjo *et al*., 2022). This index, pioneered by Hidalgo and Hausmann (2009), reflects countries' export product diversity, offering insights into export structure (Swart and Brinkmann, 2020).

The theoretical framework for analysing the environmental impacts of economic complexity combines principles from ecological economics, industrial ecology and complex systems theory. It suggests that more complex economies, marked by diverse and advanced production processes, can yield both positive and negative environmental outcomes. Increased complexity may improve resource efficiency and encourage green technology development; however, it can also result in greater energy use and resource extraction due to intensified production activities. This framework explores these interactions through the perspectives of production networks, technological innovation and regulatory settings, highlighting the importance of sustainable development strategies that harmonize economic growth with ecological sustainability. As economic complexity grows, the increased capital from product diversity can drive production ambitions that may neglect environmental considerations. However, this capital also supports energy-efficient technologies, leading to more efficient and cost-effective energy use, which positively affects environmental quality (Magazzino *et al*., 2022; Zafar *et al*., 2022).

As economic complexity rises, there is increased capital due to product variety, potentially fostering production ambitions that overlook environmental concerns. However, this increased capital is also reflected in energy inputs, promoting the adoption of energy-efficient technologies. Consequently, increasing economic complexity can lead to more efficient and cost-effective energy use, positively affecting environmental quality (Magazzino *et al*., 2022; Zafar *et al*., 2022).

The acceleration of industrialization with increasing globalization has led to global growth. Industrialization has increased by 262.54% compared to 1970 and global economic growth has increased by 349.86% in 2020 (UNCTADSTAT, 2023). However, these increases have resulted in significant environmental degradation. CO_2 emissions increased by 126.14% globally in 2020 compared to 1970, despite the availability of modern technologies (BP, 2022). Fossil fuels continue to dominate global energy use, accounting for 79.94% in 2020 (IEA, 2023). As the global population increases, the demand for energy is met primarily through fossil fuels, causing a 13.16% increase in per capita fossil fuel use in 2019 compared to 1990 (IEA, 2023). This trend could lead to disastrous consequences for the environment. To reduce dependence on foreign energy, green energy is an important alternative. Renewable energy is clean, environmentally friendly and has the highest annual average increase of 3.98% for energy use from 1990 to 2020 (Kirikkaleli *et al*., 2022). However, its share in global energy use is only 5.21% in 2020, far below the desired level. Despite its low levels, green energy is an essential alternative to reduce environmental destruction.

In the literature, globalization and environmental relations were initially highlighted by Dreher (2006). The globalization variable has multiple dimensions (economic, social and political). Increasing globalization increases investments, production and foreign trade. Economies with higher economic globalization are those that benefit more from total factor productivity and financial developments (Sulaiman *et al*., 2017). In addition, economies that want to increase foreign capital alongside domestic capital can also benefit from other positive dynamics of economic globalization (Terzi and Pata, 2020). This increased capital can lead to investments in energy-efficient technologies and environmentally friendly energy sources within the host country (Shahbaz *et al*., 2017; Yang *et al*., 2020). However, excessive resource use caused by production ambition in economies can also lead to environmental degradation due to the increasing globalization (Mehmood, 2021; Pata, 2021).

The environmental Kuznets curve serves as a framework to elucidate the correlation between economic advancement and environmental degradation. This curve illustrates that although economic progress initially leads to an increase in environmental pollution, there comes a point where environmental degradation starts to diminish as economic development progresses. Initially, economic growth may exacerbate environmental pollution through heightened industrialization and resource exploitation. Nevertheless, as an economy reaches a certain threshold, the trend reverses, with environmental pollution declining owing to the implementation of environmental regulations and advancements in technology.

The environment is affected by economic complexity, the use of green energy, fossil fuel usage and globalization, as stated previously. This study examines the inverted U-shaped relationship between these variables and air pollution for emerging economies that are dependent on foreign energy. This group of countries merits investigation for numerous reasons. Emerging economies are part of the developing countries in the upper country group that depend on foreign energy in the energy sector. These economies have high growth rates. In 2021, their GDP increased by 613.20% compared to 1990 and their share of global GDP increased from 8.11% to 23.94% (WB, 2023). The energy driving their rapid growth primarily comes from fossil fuels, which account for the largest share. Fossil fuel use and CO_2 emissions in these economies increased by 245.84% and 279.28%, respectively, in 2020 compared to 1990. In addition, their share of global fossil fuel use rose from 14.54% in 1990 to 33% in 2020. Additionally, these economies' use of fossil fuels as a proportion of total energy resources rose from 76.78% in 1990 to 85.33% in 2020, while their share of global CO_2 emissions increased from 15.09% to 37.10% during the same period. As a result, these 12 emerging economies that import energy are responsible for almost half of global environmental degradation. Thus, improving the environment in the countries would positively affect the global air quality. Moreover, all the energy imports of the economies increased by 389.12% in 2020 compared to 1990, underscoring the need for alternative energy sources that are environmentally friendly and can reduce foreign energy dependency while ensuring energy supply security. Therefore, investigating the factors affecting CO_2 emissions in these economies is crucial (IEA, 2023).

The purpose of this study is to examine the intricate relationship between economic complexity, green energy use, fossil fuel dependency, globalization and air pollution in emerging economies that rely heavily on energy imports. By investigating the inverted U-shaped relationship, commonly illustrated by the environmental Kuznets curve, this research aims to identify how these variables interact and contribute to CO_2 emissions in these rapidly growing countries. Given their substantial impact on global environmental degradation, understanding the dynamics at play in these economies is crucial for devising strategies that promote sustainable development and mitigate environmental harm. Through rigorous econometric analysis, this study aims to provide actionable insights to inform policy decisions and support a transition to sustainable energy practices and improved air quality.

The subsequent section presents the results of the econometric analysis and findings after conducting a literature review on the topic. The study concludes by providing recommendations and presenting the outcomes.

2. Literature Review

Typically, the EKC hypothesis is studied to understand the relationship between economic development and air quality. In studies testing the EKC hypothesis using economic growth, the coefficient of GDP is expected to be positive. In other words, increasing GDP increases environmental destruction (Sun *et al.*, 2024). On the other hand, there are studies using green energy and globalization when investigating environmental quality (Pata *et al.*, 2024; Kartal and Pata, 2023). Environmental quality has been expanded with variables such as geopolitical risk and economic uncertainty (Pata, Karta, Zafar, 2023a). However, the present research study focuses on exploring the relationship between economic complexity and the air and climate. It also examines the impact of fossil fuel usage, renewable energy usage and global variables on the EKC hypothesis. The literature review is organized into three sections. The first section examines the link between economic complexity and the environment. The second section explores the relationship between green and fossil energy sources and the environment. Lastly, the third section investigates the impact of globalization on the environment.

Numerous studies in the literature have highlighted various approaches to enhancing environmental sustainability. Gao and Wang (2023) emphasized the impact of the opening of high-speed railways, while Gao *et al.* (2023) suggested that digitization, alongside its numerous advantages, also reduces energy consumption, thereby providing several cost benefits (Gao, Li, Yu, 2022). Additionally, there are studies indicating that value added tax (VAT) reforms contribute to ecological innovation, which is crucial for environmental sustainability (Gao, Mo, Xiong, *et al.*, 2022). However, the relationship between economic complexity and environmental sustainability has gained increasing attention in recent years. In recent years, there has been a noticeable increase in research examining the relationship between economic complexity and the environment, with a particular focus on the EKC hypothesis. Can and Gozgor (2017) found that France's improved economic complexity led to the adoption of energy-efficient technologies and contributed to long-term environmental improvement. Similarly, Neagu and Teodoru (2019) found that economic complexity with green energy is positive for environmental destruction for EU countries. Additionally, Neagu (2019) found the curvilinear relationship between economic complexity and CO_2 to be convex for 25 EU countries. This implies that for these countries, pollution initially increases as they boost the complexity of their exported products. However, after a particular turning point, economic complexity inhibits polluting emissions. On the other hand, Yilancı and Pata (2020) found a concave relationship between income and environmental degradation for the Chinese economy. They also found that energy consumption and economic complexity are significantly responsible for environmental degradation. Ahmad, Khan, Anser, *et al*. (2021a) found evidence supporting the EKC hypothesis for China and they also discovered that increasing *FDI* and income levels reduce environmental degradation. Additionally, Boleti *et al*. (2021) found that moving towards higher economic complexity enhances environmental quality for 88 emerging economies. Chu (2021) obtained results supporting the EKC hypothesis for 118 developed/developing economies, implying that product diversity and increased production have a positive impact on environmental quality after a specific point. Pata (2021b) found that the EKC hypothesis holds for the United States and that the use of renewable energy and globalization decreases environmental degradation. However, Pata and Caglar (2021) found that the environmental Kuznets curve (EKC) hypothesis is not applicable to China. Additionally, they found that renewable energy has no impact on environmental degradation. However, Kartal and Pata (2023) found that renewable energy usage reduces environmental degradation in China. Globalization, on the other hand, contributes to environmental degradation. Similarly, Pata, Kartal, Dam *et al*. (2023) found in Latin American and Caribbean countries that globalization has a negative effect on environmental quality, while renewable energy has a positive effect. On the other hand, Eweade *et al*. (2023) found that fossil fuel usage increases environmental degradation in the Mexican economy, but globalization has no effect.

Romero and Gramkow (2021) discovered a negative relationship between economic complexity and CO_2 emissions in 67 developed and developing countries. Furthermore, Bucak (2022) obtained results supporting the EKC hypothesis for G8 countries and also found that increased economic complexity in these economies enhances economic development but at the expense of environmental pollution. Finally, Khan *et al*. (2022) found evidence supporting the EKC hypothesis for the G7 countries. Economic complexity reduces environmental degradation in the G7 countries after reaching a certain threshold level. Nonetheless, population, inflation, *FDI* and total trade intensity exacerbate environmental degradation for the G7 countries.

Numerous studies have explored the relationship between environmental quality and the use of renewable and non-renewable energy sources. For example, Lee (2013) found that promoting clean energy is crucial for economic growth in the G20 countries, leading to more investment in clean energy and ultimately decreasing CO_2 emissions. In the OECD countries, Shafiei and Salim (2014) showed that green energy usage mitigates CO_2 emissions, while non-renewable energy consumption worsens environmental degradation, supporting the EKC hypothesis. This was corroborated by Jebli *et al*. (2016) for 25 OECD countries, where green energy consumption reduced CO_2 emissions, while fossil fuel usage worsened environmental quality. Dogan and Seker (2016) reported that renewable energy use reduced CO_2 emissions in the EU, while fossil fuel consumption negatively affected environmental quality. In contrast, Jebli and Youssef (2017) discovered that clean energy usage in North African countries could increase CO_2 emissions due to their heavy dependence on polluting energy and low usage of clean energy. In the BRICS economies, Ulucak and Khan (2020) demonstrated that clean energy was an effective alternative to polluting energy in promoting air quality, while Ahmad, Muslija, Satrovic (2021) found that green energy improved environmental sustainability in 11 developing countries. Shahzad *et al*. (2021) showed that fossil fuel usage in the USA contributed to environmental degradation by increasing CO_2 emissions. In summary, with few exceptions, using green energy reduces environmental pollution, while non-renewable energy use exacerbates environmental degradation in line with the EKC hypothesis.

The potential benefits of globalization in reducing CO_2 emissions through improved cultural, political and social welfare are widely recognized. However, the negative impact of increased competition and production goals on environmental degradation is often overlooked. This section focuses on exploring the relationship between the overall economic globalization index (*KOF* index) and air quality.

Wang *et al*. (2019) found that globalization has a significant impact on reducing CO_2 emissions for 137 countries. However, in less developed countries, ecological inequality occurs, resulting in more air pollution. Salahuddin *et al*. (2019) found that increasing globalization in Sub-Saharan African countries reduces CO_2 emissions. Similarly, Bilal *et al*. (2021) found that One Belt One Road countries experience an improvement in environmental quality due to globalization, as it has led to a decrease in CO_2 emissions by increasing access to modern energy-efficient technology, advanced production processes and governance skills. For Saudi Arabia, Xu *et al*. (2018) found that globalization reduces environmental degradation. In the South Asian countries of Nepal, Afghanistan, Bangladesh and Sri Lanka, Mehmood and Tariq (2018) found a U-shaped relationship between globalization and CO_2 emissions, while an inverted U-shaped relationship was observed in Pakistan and Bhutan. In Bangladesh and Nepal, globalization increases CO_2 emissions, while in Pakistan and Bhutan, globalization reduces them. In contrast, Farooq *et al*.

(2022) found that economic globalization is harmful to environmental sustainability in 180 countries. However, Aluko *et al*. (2021) found that in 27 selected industrialized countries, globalization plays a positive role in the environment by facilitating the transfer of green technologies and increasing environmental awareness. Overall, there is no consensus on the general impact of globalization on the environment.

Table 1: Literature summary

Author(s)	Period/ sample	Method	Variables	Results
Lee (2013)	1971–2009/ G20 countries	Fixed effects	CO_2, *GDP*, *FDI*, *EC*, *REC*	*GDP* (–), *FDI* (+), *EC* (+), *REC* (+)
Shafiei and Salim (2014)	1980–2011/ OECD countries	STIRPAT model	CO_2, *POP*, *GDP*, *REC*, *NREC*	*POP* (+), *REC* (–), *NREC* (+)
Dogan and Seker (2016)	1980–2012/ European Union	DOLS	CO_2, *GDP*, *REC*, *NREC*, *TRD*	EKC (valid), *REC* (–), *NREC* (+), *TRD* (–)
Jebli *et al.* (2016)	1980–2010/ 25 OECD countries	FMOLS, DOLS	CO_2, *GDP*, *REC*, *NREC*, *EXP*, *IMP*	EKC (valid), *REC* (–), *NREC* (+), *EXP* (–), *IMP* (–)
Can and Gozgor (2017)	1964–2014/ France	DOLS	CO_2, *GDP*, *EC*, *ECI*	EKC (valid), *EC* (+), *ECI* (–)
Jebli and Youssef (2017)	1980–2011/ five North African countries	OLS, FMOLS, DOLS	CO_2, *GDP*, *NREC*, *AGR*	*GDP* (+), *NREC* (+), *AGR* (–)
Mehmood and Tariq (2018)	1972–2013/ South Asian countries	ARDL	CO_2, *KOF*	EKC (valid)
Xu *et al.* (2018)	1971–2016/ Saudi Arabia	ARDL	CO_2, *FD*, *EC*, *URB*, *GDP*	*FD* (+), *EG* (+), *URB* (–), *GDP* (+)
Neagu (2019)	1995–2017/ 25 selected European Union (EU) countries	FMOLS, DOLS	CO_2, *ECI*, *EI*	EKC (valid), *EI* (+),
Neagu and Teodoru (2019)	1995–2016/ 25 EU countries	FMOLS, DOLS	*GHG*, *EC*, *ECI*	*ECI* (–), *EC* (+)
Salahuddin *et al.* (2019)	1984–2016/ 44 Sub-Saharan Africa countries	MG, AMG, CCEMG, PMG	CO_2, *URB*, *KOF*, *GDP*, *EC*	*GDP* (+), *EC* (+), *URB* (+), *KOF* (–)
Wang *et al.* (2019)	1970–2014/ 137 countries	pooled OLS regression	CO_2, *KOF*, *URB*, *SS*	*KOF* (+), *URB* (+), *SS* (–)
Ulucak and Khan (2020)	1992–2016/ BRICS economies	FMOLS, DOLS	*ECF*, *GDP*, *REC*, *NRR*, *URB*	EKC (valid), *REC* (–), *NRR* (–), *URB* (–)
Yilancı and Pata (2020)	1965–2016/ China	Fourier ARDL	*EF*, *GDP*, *EC*, *ECI*	EKC (Invalid), *EI* (+), *EC* (+), *ECI* (+)
Ahmad, Khan, Anser, *et al.* (2021)	2005–2018/ China (31 provinces)	DCCEMGT	CO_2, *POP*, *IA*, *EC*,	EKC (valid), *IA* (+), *POP* (–)

Ahmad, Muslija, Satrovic (2021)	1992–2014/ 11 developing countries	FMOLS, PMG	CO_2, *GDP*, *ELC*	EKC (valid), *ELC* (+)
Bilal *et al.* (2021)	1991–2019/ One Belt One Road (OBOR) countries	FMOLS, DOLS	CO_2, *KOF*, *GDP*, *TI*, *ICT*	*KOF* (+), *GDP* (+), *TI* (–), *ICT* (+)
Boleti *et al.* (2021)	2002–2012/ 88 developed and developing countries	Fixed-effects two-stage least squares/ instrumental variables	*EPI*, *ECI*, *GDP*, *POP*	*ECI* (–), *EC* (+), *ECI* (+), *POP* (–), *AGR* (–), *IND* (–), *COR* (–), *TRD* (+), *EDU* (–), *URB* (–)
Chu (2021)	2002–2014/ 118 countries	GMM	CO_2, *ECI*, *INS*, *GDP*, *GFCG*, *IND*, *REC*	EKC (valid), *INS* (–), *GDP* (+), *GFCG* (+), *IND* (+), *REC* (–)
Pata (2021a)	1980–2016/ USA	VECM	*EF*, CO_2, *ECI*, *KOF*, *REC*, *NREC*	EKC (valid), *REC* (–), *NREC* (+), *KOF* (+)
Pata and Caglar (2021)	1980–2016/ China	Augmented ARDL	*EF*, CO_2, *GDP*, *KOF*, *REC*, *TRD*, *HC*	EKC (Invalid), *KOF* (+), *REC* (+), *TRD* (–), *NREC*
Romero and Gramkow (2021)	1976–2012/ 67 countries	OLS regression	*EI*, *ECI*, *TRD*, *URB*, *EC*, *GDP*, *POP*, *EDU*, *AGR*, *MNF*, *PTN*	*ECI* (–),*TRD* (+), *URB* (+), *EC* (+), *GDP* (–), *POP* (+), *EDU* (+), *AGR* (+), *MNF* (+), *PTN* (+)
Shahzad *et al.* (2021)	1965–2017/ USA	Quantile autoregressive distributed lag (QARDL)	*EF*, *ECI*, *EC*	*ECI* (+), *EC* (+)
Farooq *et al.* (2022)	1980–2016/ 180 countries	POLS	CO_2, *GDP*, *EC*, *URB*, *KOF*	EKC (valid), *EC* (+), *URB* (+), *KOF* (–)
Khan *et al.* (2022)	1996–2019/ G7 countries	Fully-modified OLS and dynamic OLS	*EF*, *ECI*, *REC*, *NREC*, *GDP*, *POP*, *INF*, *FDI*, *INQ*, *TRD*	EKC (valid), *REC* (–), *NREC* (+), *GDP* (+), *POP* (+), *INF* (+), *FDI* (+), *INQ* (–), *TRD* (+)
Eweade *et al.* (2023)	1975–2020/ Mexico	ARDL, NARDL	*EF*, *GDP*, *NREC*, *FDI*, *KOF*	*GDP* (+), *NREC* (+), *FDI* (–), *KOF* (+)
Kartal and Pata (2023)	1990–2020/ China	Novel quantile-on-quantile regression, nonparametric causality in quantiles and quantile regression methods	CO_2, *ECF*, *LCF*, *REC*, *KOF*, *TEI*	CO_2, *REC* (–), *KOF* (+), *TEI* (+)
Pata *et al.* (2023b)	1990–2018/ Latin American and Caribbean countries	Panel ARDL	*LCF*, *KOF*, *GDP*, *REC*, *TRD*	*REC* (+), *KOF* (–), *TRD* (+)

Note: *GHG*: generating air pollution, *POP*: population, *IA*: industrial agglomeration, *EC*: energy consumption, *EPI*: environmental performance, *ECI*: economic complexity index, *AGR*: agriculture, *IND*: industry, *COR*: corruption, *TRD*: trade, *URB*: urban, *EDU*: education, *GFCG*: gross fixed capital formation, *INS*: institutions, *HC*: human capital, *ECF*: global hectares, *LCF*: *BIO/ECF*, *TEI*: technological innovation, *FDI*: foreign direct investment, *MNF*: manufacturing, *PTN*: patent, *INF*: inflation, *INQ*: income inequality, *EXP*: export, *IMP*: import, *NRR*: natural resource rent, *ELC*: electric power consumption, *SS*: service sector, *ICT*: information and communication technologies, *FD*: financial development, *EF*: ecological footprint.

Source: Authors' own elaboration

3. Methodology

3.1 Variables and data

The study employs panel data from 12 emerging countries heavily reliant on energy imports, covering the period from 1996 to 2020. While selecting the countries, the energy import and energy export values of the countries among the 23 emerging economies in the IMF's 2015 World Economic Forum were examined during the 1996–2020 period. During this period, countries with energy import values exceeding their energy export values were selected. In addition, in order to use balanced panel data and ensure parallelism for all the countries, the start and end of the data for all the countries were selected to be 1996 and 2020 as the most recent. The primary method used to estimate the models was the autoregressive distributed lag (ARDL) model. The explanatory variables used in the model were CO_2 emissions per capita (measured in tonnes), clean energy use per capita (including hydro, wind, solar, *etc*., measured in koe), non-renewable energy use per capita (including coal, oil and natural gas measured in koe), the overall economic globalization index (*KOF* index) and the economic complexity index (which measures the diversity of goods produced by economies). The data for CO_2 emissions, renewable energy and fossil energy use were obtained from the International Energy Agency (IEA), while the economic complexity index and the economic globalization index were sourced from the Swiss Institute of Economics. All the variables were transformed into logarithmic form. The study's findings are presented through econometric analysis, concluding with recommendations derived from the results.

3.2 Dynamic model

This study examines the correlation between CO_2 emissions, economic complexity, economic globalization, renewable energy use and fossil energy use. To accomplish this, the researchers utilized a dynamic panel model that employed suitable tools and context to predict varied data. Three estimators, including ARDL and parameters p and q, were used to predict the data characteristics. The MG (mean group) and PMG (pooled mean group) models of Pesaran and Smith (1995) and Pesaran *et al*. (1999) were employed and DFE (dynamic fixed-effects) estimation was also conducted using these estimators. The ARDL model was used for this study. The model determined by Loayza and Ranciere (2006) is taken as reference.

$$\Delta\left(y_i\right)_t=\sum_{j=1}^{p-1}\gamma_j^i\,\Delta\left(y_i\right)_{t-j}+\sum_{j=0}^{q-1}\delta_j^i\,\Delta\left(X_i\right)_{t-j}+\varphi^i\left[\left(y_i\right)_{t-1}-\left\{\beta_0^i+\beta_1^i\left(X_i\right)_{t-1}\right\}\right]\varepsilon_{it}\dots \quad (1)$$

In the equation, the dependent variable CO_2 emission is represented by y. The variable X includes economic complexity, green energy use per person, fossil energy use per person and economic globalization. The short-term coefficients are γ and δ, while the long-term coefficients are β. Balancing is important for the long term. A ratio is used for this. This ratio is denoted with the symbol φ. The units and time are represented by i and t, respectively. The expressions in square brackets [...] indicate long-term growth regression. The panel ARDL method can be employed to calculate the PMG, MG and DFE estimators in the equation. This method includes a long-term dynamic process. The PMG, MG and DFE models are used for this. Additionally, the study examines the heterogeneity of slope coefficients, as outlined by Demetriades et al. (2006).

According to previous studies by Johansen (1995), Phillips and Hansen (1990) a long-term relationship can only exist if the degrees of stability are equal. However, the PMG and MG estimation techniques are newer and have shown many benefits over traditional approaches, as highlighted by Pesaran and Shin (1995). One key advantage is the removal of stationarity degree rigidity for long-term relationships, meaning that it is valid for variables with either I(1) or I(0). Additionally, the PMG and MG techniques are suitable for small N and T models. With these techniques, it is possible to estimate both short-term and long-term effects simultaneously using the ARDL model. In contrast, the use of the technique of Engle and Granger (1987) may result in internality problems, which can be overcome with the ARDL method.

3.3 PMG, MG and DFE estimators

The PMG estimator is selected as the primary estimation method in this study for its important features. The slopes for the short term are heterogeneous and are taken into account. It also combines the magnitude of long-term disequilibrium recovery with residual variances. However, the homogeneity of long-term effects is limited. To ensure efficiency, consistency, and validity, the error correction coefficient (ECT) must be both negative (−) and statistically significant, signaling a long-term relationship among the variables. Consistency in the PMG estimator necessitates treating the series as uncorrelated, achieved by considering the explanatory variables as exogenous in the error correction form and incorporating appropriate ARDL (p, q) lags for both dependent and explanatory variables. The relative sizes of time (T) and sample size (N) are also important in addressing heterogeneity and bias in the dynamic model. Teal and Eberhardt (2010) stated in their study that the heterogeneity of slopes is important for a better understanding of the growth process of an economy. Thus, PMG is a necessary estimator for this study.

The second estimation method used in this study is the MG estimator suggested by Pesaran and Smith (1995). The MG estimator estimates a separate regression for each unit and obtains coefficients as a result of these regressions. However, these coefficients are unweighted averages and there are no restrictions. MG provides distinct short-term and long-term coefficients for each unit, resulting in heterogeneity across all units in both short and long runs. Additionally, consistency and validity must be met while conducting the study. MG is important for this, because the unit and time available for the study are sufficient.

In this study, the DFE (dynamic fixed-effects) method is used as an alternative approach for estimation. It is similar to the PMG method, but with the restriction that the cointegration vector coefficient remains uniform across all panels in the long term. In contrast, the PMG method allows for heterogeneity in the short term and homogeneity in the long term. In this study, the Hausman test was used to take into account problems such as endogeneity and bias (Blackburne and Frank, 2007; Baltagi *et al*., 2000).

The DFE method is another approach used in this study for estimation. It shares similarities with the PMG method, but with the restriction that the cointegration vector coefficient is uniform across all panels in the long term. In contrast, the PMG method exhibits heterogeneity in the short term and homogeneity in the long term. Additionally, options to evaluate standard errors and clustering correlation are provided by DFE. However, DFE is an important estimator. This importance is related to the possibility of bias due to the endogeneity problem. To address this issue, the Hausman test is employed as a means of determining the extent of this internality.

In summary, the PMG estimator is considered superior to the MG estimator in terms of long-term homogeneity. The selection of the most appropriate estimator among PMG, MG and DFE is determined using the Hausman test. According to the null hypothesis, PMG is preferred over MG. Similarly, DFE is preferred over MG. If MG is not preferred here, the choice will be between PMG and DFE. PMG is more dominant than DFE.

4. Empirical Results

4.1 Statistics and correlation of data

Table 2 presents information on all the variables used in the model. The average air quality value falling within the range of [−6, −5] suggests that there is some level of fluctuation in CO_2 emissions. Furthermore, the significant standard deviation of 0.300 in CO_2 emissions indicates that there are considerable differences between countries. This finding suggests that countries heavily dependent on energy imports and exhibiting high growth rates are significantly impacted by energy prices and crises. As a result, there is an increase in the environmental quality of these countries. Conversely, the maximum and minimum values of renewable energy use averaging 1.674 and the highest standard deviation highlight that the sample countries do not take full advantage of this energy source. Fossil fuels, with an average of 2.996, indicate that the countries rely heavily on this energy source, creating a significant environmental problem. Moreover, although globalization may have positive effects on these countries, the low usage of renewable energy and the high reliance on fossil fuels affect CO_2 emissions negatively.

Table 2: Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. dev.	Observations
CO_2	–5.552	–5.444	–5.052	–6.192	0.300	345
ECI	0.278	0.333	0.562	–2.000	0.218	345
ECI^2	0.125	0.112	4.000	0.000	0.239	345
REN	1.674	1.808	2.414	0.691	0.385	345
FOS	2.996	3.131	3.418	2.371	0.306	345
KOF	1.752	1.759	1.943	1.526	0.101	345

Note: The variables in this study have a time (*T*) period of 23 and are observed across 15 units (*N*). The total number of observations, represented by *NT*, is thus 345.

Source: Authors' own calculations

The correlation coefficients are placed in Table 3. When these coefficients are examined, low correlations are seen. This means that the variables of the model have a good fit. Moreover, the low correlation values play a significant role in mitigating the issue of multicollinearity. Consequently, these low values strengthen the robustness of the model outcomes.

Table 3: Correlation matrix

Correlation *t*-statistic	***ECI***	***REN***	***FOS***	***KOF***
ECI	1 (–)	–	–	–
REN	–0.068 (–1.173)	1 (–)	–	–
FOS	0.434*** (8.316)	0.066 (1.134)	1 (–)	–
KOF	0.224*** (3.973)	0.098* (1.691)	0.401*** (7.552)	1 (–)

Notes: The upper values represent the strength of correlation and are denoted by *t*-statistics (in parentheses); ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Source: Authors' own calculations

4.2 Panel unit root test

This section presents descriptive statistics to provide an overview of the data. Table 2 displays the descriptive statistics for the variables. When the elasticity values of all the variables are examined, the average of environmental quality is negative. In addition, air quality (CO_2 emissions) has the closest minimum and maximum values. Fossil fuels have the exact opposite. The clean energy use series demonstrates the highest volatility. In this study, PMG was preferred for the long-term coefficient relationship. For this, the integrated degrees of the variables are important. So are the variables I(1) or I(0). Thus, it is crucial to assess the stationarity level of the variables using two stationarity tests introduced in the literature by Im *et al*. (2003) and Maddala and Wu (1999).

Table 4 shows the results of the stationarity tests conducted on the variables. The table indicates that all the variables have unit roots in their level values. However, after applying the first difference, all the variables were found to be stationary. Thus, since all the variables are I(1), the ARDL dataset is estimated using the appropriate technique.

Table 4: Unit root test results for variables

	Levels		First differences	
Variables	**IPS**	**MW**	**IPS**	**MW**
CO_2	–0.550	27.664	–12.407***	169.557***
ECI	–1.333*	30.649	–6.634***	92.396***
ECI^2	0.585	27.104	–6.785***	115.023***
REN	1.618	22.416	–12.592***	170.195***
FOS	–1.619*	34.086*	–10.762***	144.770***
KOF	0.293	24.211	–9.554***	134.511***

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

Source: Authors' own calculations

In this section, three estimators are used and compared: PMG, MG and DFE. The selection of the appropriate estimator is determined by conducting the Hausman test. If the *p*-value of the test exceeds 0.05, it is concluded that either DFE or PMG is the more effective and consistent estimator, depending on the tested hypotheses (H_0: The DFE estimator is more effective and consistent than the MG estimator, or H_0: The PMG estimator is more efficient and consistent than the MG estimator). The DFE estimator assumes equal adjustment coefficients in the short/

long term. However, according to the Hausman test result, the probability value will determine the estimator. If the p-value is greater than 5%, PMG will be preferred. Otherwise, the estimator is MG. Conversely, if the p-value is less than 0.05, it is determined that the MG estimator is more effective (H_a: Heterogeneity; long-term parameters vary across the units).

Table 5: Hausman test for MG, PMG and DFE

Variables	Coefficients			Differences of coefficients		Standard errors of differenced coefficients	
	(A)	(B)	(C)	(A-B) difference	(A-C) difference	Sqrt (diag(V_A-V_B)) SE	Sqrt (diag(V_A-V_C)) SE
	MG	PMG	DFE				
ECI	0.145	3.058	0.205	−2.914	−0.061	1.054	409.170
ECI²	−0.211	−3.661	−0.392	3.450	0.181	0.818	317.521
REN	−0.040	−0.040	0.004	−0.0001	−0.044	0.087	33.785
FOS	1.084	1.041	0.971	0.043	0.113	0.019	8.407
KOF	0.058	0.177	0.016	−0119	0.042	0.060	29.837
MG-PMG					**MG-DFE**		
H_0: *PMG* is more effective than *MG*.					H_0: *DFE* is more effective than *MG*.		
$\chi_h{}^2{}_{(8)}$ = (A – B)'[(V_A – V_B) ^ (–1)] (A – B) 3.33					$\chi_h{}^2{}_{(8)}$ = (A – C)'[(V_A – V_C) ^ (–1)] (A – C) = 0.01		
Prob > $\chi_h{}^2$ = 0.650					Prob > $\chi_h{}^2$ = 0.9999		

Source: Authors' own calculations

Based on the results of the Hausman test presented in Table 5, it is concluded that PMG is the effective estimator, as the probability value (Prob > $\chi_h{}^2$) for MG-PMG is 0.650, which is greater than 0.05. Similarly, based on the MG-DFE test results, DFE is found to be the effective estimator with a probability value of 0.999. However, here the PMG estimator is more suitable for interpretation. In addition, Hausman $\chi_h{}^2$ values are greater than the critical values.

The results in Table 6 indicate that the PMG estimator, assuming parameter heterogeneity across units except for the long-term parameter, is interpreted. The ECT coefficient, representing cointegration and the speed of adjustment to long-term equilibrium, aligns with expectations. The ECT coefficient was obtained as −0.207. The interpretation of this is that a deviation of approximately 0.21% will be corrected in one year.

Table 6: PMG, MG and DFE results

Variables	PMG	MG	DFE
ECI	3.058***	0.144	0.205**
ECI²	−3.661***	−0.211	−0.392**
REN	−0.040**	−0.040	0.004
FOS	1.041***	1.084***	0.971***
KOF	0.177***	0.058	0.016
ECT	**−0.207****	**−0.806*****	**−0.440*****
Δ*ECI*	−1.151	−0.433	−0.081*
Δ*ECI²*	1.483	0.708	0.186**
Δ*REN*	−0.041	0.002	−0.003
Δ*FOS*	0.676***	0.116	0.542***
Δ*KOF*	0.094	0087	−0.019
Constant	−1.974**	−6.966	−3.749***

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

Source: Authors' own calculations

When the prediction results were examined, long-term results for PMG were statistically significant. The study indicates that using renewable energy has a positive effect on reducing CO_2 emissions, whereas the use of fossil fuels has the most significant impact on environmental pollution. Furthermore, economic complexity and globalization are linked to an increase in CO_2 emissions. The coefficient analysis indicates that a 1% increase in clean energy use leads to a 0.04% reduction in air pollution in the long run. In contrast, a 1% increase in globalization, economic complexity and fossil fuel consumption leads to a 0.18%, 3.058% and 1.04% increase in air pollution, respectively. These findings imply that relying solely on green energy will not be sufficient to address air quality since the benefits of clean energy cannot counteract the negative effects of fossil fuels. In addition, the energy industry's inefficient technologies and high reliance on fossil fuels in developing countries put enormous pressure on the environment. The findings support the results of previous studies (Sharif *et al*., 2023; Pata, 2021; Destek, 2022; Kirikkaleli *et al*., 2022, Zafar *et al*., 2022) that revealed the impact of green and fossil fuel use on CO_2 emissions. However, the results of Pata (2018) and Yu *et al*. (2022) are inconsistent with the outcomes for Turkey and France, respectively.

However, empirical evidence suggests that globalization leads to an increase in CO_2 emissions. It is expected that increasing globalization would reduce CO_2 emissions by promoting information sharing, technology transfer and the use of efficient energy production methods (Saud *et al*., 2020; Destek, 2022). However, emerging economies that are heavily reliant on energy imports have economies that are more closely tied to fossil fuels. In 1990, emerging economies accounted for 76.78% of total energy consumption (coal 43.69%, oil 24.49% and natural gas 8.61%), while this share increased to 85.33% (coal 51.70%, oil 21.53% and natural gas 12.10%) in 2020 (IEA, 2023). Therefore, increasing globalization in emerging economies not only leads to increased productivity but also increases energy demand. This demand is met primarily by fossil fuels, which results in increased CO_2 emissions. Thus, while globalization is important for emerging economies, it also has a polluting effect. In addition, the GDP of emerging economies increased by 613.20% in 2021 compared to 1990 (WB, 2023), but energy imports increased by 389.12% during the same period. This indicates that emerging economies rely heavily on imported energy to support their GDP and are highly integrated with fossil fuels. Therefore, environmental quality will continue to be a relevant issue for emerging economies in the future.

The results from PMG, MG and DFE estimations indicate that the square of the *ECI* coefficient has a negative sign, implying that the EKC hypothesis holds true for energy-importing emerging countries. This suggests that air pollution initially increases (+) with economic complexity and then decreases (−) after reaching a certain point. These findings are consistent with the results reported by several studies (Jebli *et al*., 2016; Ulucak and Khan, 2020; Chu, 2021; Pata (2021b); Khan *et al*., 2022). However, the results for China in Yilanci and Pata (2020), Indonesia in Massagony and Budiono (2022) and Turkey in Alola and Donve (2021) are inconsistent with these findings. This could be due to the use of economic complexity instead of economic development and the use of CO_2 emissions instead of ecological footprint.

Furthermore, the short-term results presented in Table 6 show similar outcomes to the long-term results. While the use of green energy reduces CO_2 emissions in the short run, economic complexity, globalization and fossil fuel use increase environmental degradation. However, variables other than fossil fuel use were statistically insignificant.

Table 7 presents the estimated short-term coefficients for each country. Analysing the short-term results allows a more detailed investigation of the characteristics of each country and comparison with the long-term findings.

Table 7: Short-term country-specific coefficient estimates

Countries	*ECT*	*ECI²*	*ECI*	*FOS*	*REN*	*KOF*	C
Argentina	−0.004 (0.032)	0.073 (0.786)	−0.071 (0.392)	0.811*** (0.092)	0.049 (0.038)	−0.104** (0.045)	−0.034 (0.303)
Bulgaria	−0.695*** (0.142)	14.563** (5.856)	−9.951** (3.997)	0.333** (0.137)	0.047*** (0.015)	0.073 (0.060)	−6.603*** (1.252)
Chile	−0.050 (0.063)	−1.106 (1.860)	0.434 (0.783)	0.760*** (0.149)	−0.105* (0.057)	−0.197* (0.119)	−0.461 (0.592)
China	−0.130 (0.120)	1.099 (1.264)	−0.740 (0.928)	0.764*** (0.200)	0.020 (0.063)	0.121 (0.103)	−1.231 (1.115)
Hungary	0.009 (0.059)	−1.175** (0.497)	0.842** (0.375)	0.761*** (0.075)	−0.043 (0.050)	−0.117 (0.124)	0.088 (0.566)
Mexico	−1.139*** (0.200)	3.387* (1.878)	−2.687* (1.445)	−0.506 (0.459)	0.060 (0.185)	0.418 (0.489)	−10.908*** (1.920)
Pakistan	−0.006 (0.013)	0.675 (0.667)	−0.129* (0.068)	1.293*** (0.156)	−0.099* (0.052)	−0.105 (0.065)	−0.050 (0.120)
Peru	−0.022 (0.028)	−1.285*** (0.429)	−0.167 (0.123)	0.664*** (0.123)	−0.326** (0.139)	0.119 (0.249)	−0.200 (0.251)
Philippines	−0.012 (0.048)	0.139 (0.252)	−0.016 (0.147)	0.880*** (0.108)	−0.104 (0.076)	0.415*** (0.151)	−0.116 (0.452)
Romania	−0.343 (0.141)**	1.122** (0.564)	−1.030** (0.453)	0.647*** (0.142)	−0.007 (0.025)	0.227*** (0.086)	−3.275** (1.295)
Thailand	−0.068** (0.028)	0.213 (0.175)	−0.217** (0.103)	0.788*** (0.077)	0.010 (0.014)	0.202* (0.110)	−0.662** (0.265)
Turkey	−0.024 (0.039)	0.086 (0.162)	−0.085 (0.160)	0.921*** (0.097)	0.013 (0.037)	0.080 (0.130)	−0.232 (0.364)

Note: ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. The standard errors of the coefficients are placed in parentheses.

Source: Authors' own calculations

Table 7 provides information on the short-term coefficients for each country, which can be used to examine specific country-level characteristics. The results indicate that in many countries, the use of clean energy has a significant negative impact on CO_2 emissions. However, Peru was the only country where this impact was statistically significant in a positive direction. Conversely, the use of polluting energy had a statistically significant positive (+) impact on CO_2 emissions in all the economies except Mexico, suggesting that higher reliance on fossil fuels and lower use of renewable energy affect CO_2 emissions negatively in these countries. In countries such as Argentina, Hungary, Chile and Pakistan, economic globalization has a positive impact on environmental quality, leading to increased use of clean energy and more efficient technologies.

5. Conclusion

Despite the availability of modern technology, fossil fuels still dominate the energy mix, particularly in developing economies, which constitutes the majority of the global population. This is a cause for concern as these countries often lack adequate technological infrastructure, resulting in environmental degradation caused by the high usage of fossil fuels. Consequently, several empirical studies have been conducted to investigate the relationship between different variables and their impact on the environment. This study sought to contribute to this endeavour by examining the effects of economic complexity, globalization, clean energy consumption and fossil fuel usage on air pollution in emerging economies that import energy for the period between 1996 and 2020.

The study addressed a gap in the literature by examining the relationship between the economic complexity index (*ECI*) and environmental degradation indicators in emerging economies, employing panel datasets and country-specific techniques. By utilizing a comprehensive dataset and diverse analytical methods across a significant number of countries, the study yielded more reliable and comprehensive findings compared to previous research on the environmental Kuznets curve (EKC) hypothesis in similar contexts.

The empirical findings suggest that renewable energy adoption offers both short-term and long-term benefits in reducing CO_2 emissions in emerging economies. This underscores the potential for further investigation in these countries, as renewable energy adoption may be more feasible due to their higher annual growth rates, positioning them as significant contributors to the global economy. Furthermore, the study highlighted the role of technological and capital advancements in fostering competition and production, potentially leading to the adoption of more energy-efficient technologies that consume less energy to produce the same output. Additionally, the increased utilization of green energy can mitigate external costs and diminish environmental deterioration.

However, previous research has revealed a negative correlation between renewable energy use and environmental quality in EU countries (Dogan and Seker, 2016), BRICS countries (Ulucak and Khan, 2020) and 11 developing economies (Ahmad *et al*., 2021). Additionally, our study identifies polluting energy sources as significant contributors to environmental degradation, consistent with findings reported for OECD countries (Shafiei and Salim, 2014), the EU (Doğan and Şeker, 2016) and the USA (Shahzad *et al*., 2021). Our key findings indicate that as globalization increases, so does energy demand, primarily met by polluting energies, negatively affecting air quality. This observation aligns with previous studies (Wang *et al*., 2019; Mehmood and Tariq, 2020; Farooq *et al*., 2022).

This study makes a significant contribution to the EKC literature by examining the relationship between the economic complexity index (*ECI*) and environmental deterioration indicators in emerging economies dependent on energy imports. Unlike previous research, this study focused on a specific group of countries, revealing a U-shaped relationship between *ECI* and air pollution, which supports the EKC theory. This finding indicates that these economies initially experience increased environmental pollution as they develop and export more complex products, reaching a peak before eventually experiencing a decline in pollution as their economic complexity helps reduce emissions. The study results demonstrate that this relationship holds in both the short and long term.

Policy recommendations from this study are diverse, addressing both immediate and long-term needs. In the short term, it is crucial for policymakers to invest in renewable energy infrastructure and encourage adoption of clean energy technologies to reduce CO_2 emissions. Additionally, reducing reliance on fossil fuels by phasing out subsidies and implementing carbon pricing mechanisms is essential for promoting sustainable energy practices. In the long term, fostering economic diversification and technological innovation is vital for decoupling economic growth from environmental degradation. Governments should prioritize R&D initiatives to enhance energy efficiency and promote sustainable production methods. Moreover, strengthening international cooperation and sharing knowledge of clean energy technologies can speed up the transition to a low-carbon economy.

The study highlights the need to consider social, political and economic variables from multiple perspectives when investigating the EKC hypothesis. Since the studied countries are energy importers, incorporating energy prices would provide valuable insights. Using export values as a substitute for the economic complexity index would also enrich the EKC literature. To address the complex relationship between economic complexity and environmental degradation, policymakers should adopt a comprehensive approach that takes advantage of economic diversification and technological innovation. This involves incentivizing investments in R&D for energy-efficient technologies, fostering industries that enhance economic complexity and promoting resource efficiency. Creating a supportive regulatory environment, providing access to financing and improving education to cultivate a skilled workforce are essential steps. Additionally, international cooperation should be strengthened to facilitate transfer of green technologies through trade agreements that prioritize sustainable development. Implementing robust carbon pricing mechanisms and phasing out fossil fuel subsidies can align economic incentives with environmental goals, encouraging adoption of cleaner technologies. By integrating these strategies, policymakers can ensure that economic complexity contributes to sustainable growth, balancing economic development with environmental preservation.

Overall, the findings of this study emphasize the urgent need for coordinated efforts from policymakers, industry stakeholders and international organizations to tackle the complex challenges of climate change and environmental degradation. By implementing evidence-based policies that prioritize renewable energy adoption, reduce fossil fuel dependency, and promote sustainable development, emerging economies can progress towards a greener and more resilient future.

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