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Economic Complexity, Green Technologies and Environmental Degradation in World's Top Polluting Countries: Evidence from Advance Panel Estimation

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ABSTRACT

The current study empirically probes into the role of economic complexity and green technologies on environmental degradation under STIRPAT framework in world's top polluting countries over 2000 to 2020 period. To empirically analyze the relationships, Common Correlated Effects Mean Group (CCEMG) estimation technique is used because of the existence of the cross sectional dependence issue in panel data. The findings reveal that economic complexity increases but green technologies decrease CO2 emissions in studied economies. By providing the comprehensive understanding on the relationship between green technologies, economic complexity and CO2 emissions, the present study recommends the governments of the concerned countries to implement relevant policies and practices for improving the production structure and foster the research and development activities to promote the development and use of green technologies to curb CO2 emissions in studied economies.

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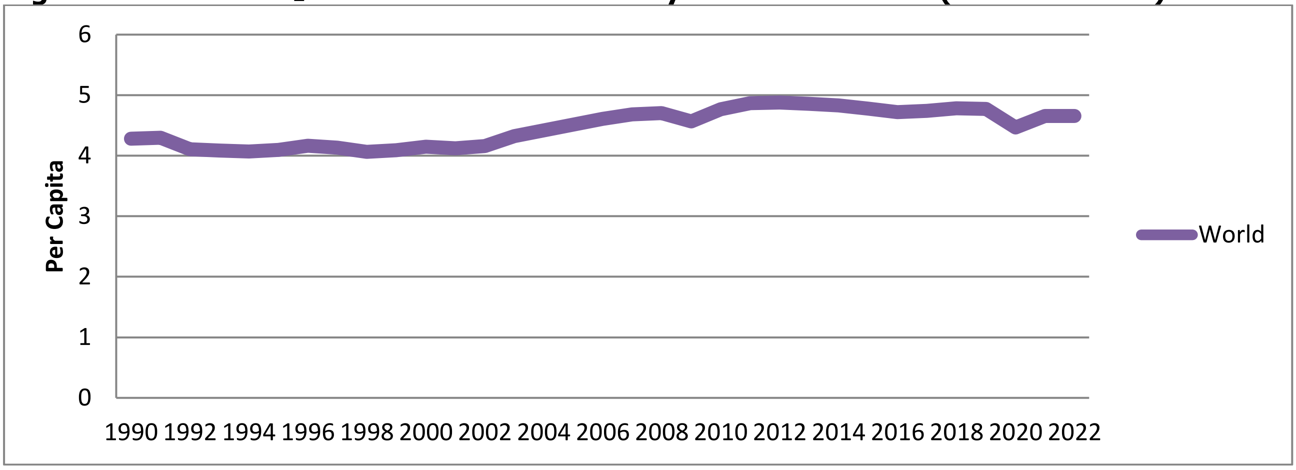
1. Introduction

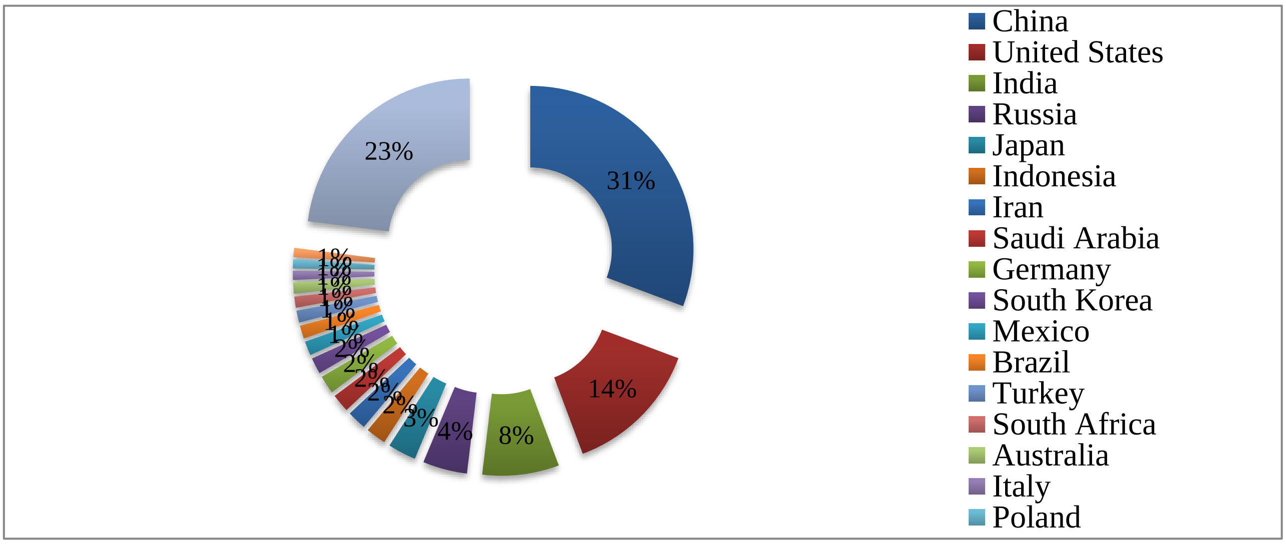
The alarming rate of the degradation of natural environment is one of the major economic challenges faced by both the environmentalists and economists. Environmental degradation refers to the deterioration of the environmental quality through natural resource depletion such as soil, air, water, the wildlife extinction and ecosystem destruction. It refers to any disturbance or change to the environment supposed to be undesirable or deleterious (Tyagi, Garg, & Paudel, 2014). Environmental degradation is one of the main issues affecting the global economy which has contributed to a number of grave issues for the planet including low living standards, natural disasters and climate change (Sheng, Meng, & Akbar, 2023). All developed and developing countries are facing varying sea level and weather patterns which seriously disturb structure of the economies and people's lives (Khan & Ximei, 2022). Among the major responsible factors, the release of greenhouse gases (GHG) is considered to be the main contributor to the degradation of the environment which has long term adverse impacts on human wellbeing. Since industrial revolution, the rise in GHG emissions has been augmenting global warming by 1.6^0 Fahrenheit, which is a very alarming condition for life on earth. Among all GHGs, CO_2 emissions stand as the key polluter accounting approximately 75% of GHG emissions and therefore require urgent attention for sustaining the environmental quality Behera et al. (2024); (Xie & Jamaani, 2022). The world has seen rapid increase of CO_2 emissions from 9.147 to 33.798 billion tons over past three decades as evident in Figure 1. The dependence of all developing and developed countries on energy in quest of the economic development is one of the main causes of this exacerbated CO_2 emissions (Dash et al., 2024). Among them, the top polluting countries are the major contributors accounting for approximately 77% of the global CO_2 emissions, while rest of the world emits only 23% Global Carbon Atlas (2021). These countries are ranked among high GDP countries, according to a recent estimate, contributing approximately 77% of the global GDP in 2023 (Statista, 2024). The pie chart in Figure 2 provides the information about CO_2 emissions by these top polluted countries, here China, USA and India had a major share of 31%, 14% and 8% followed by Russia and Japan with 4% and 3% share of CO_2 emissions globally.

Figure 1: Global CO_2 emissions from Industry and Fossil Fuels (1990 to 2022)



Source: Our World in Data (2024)

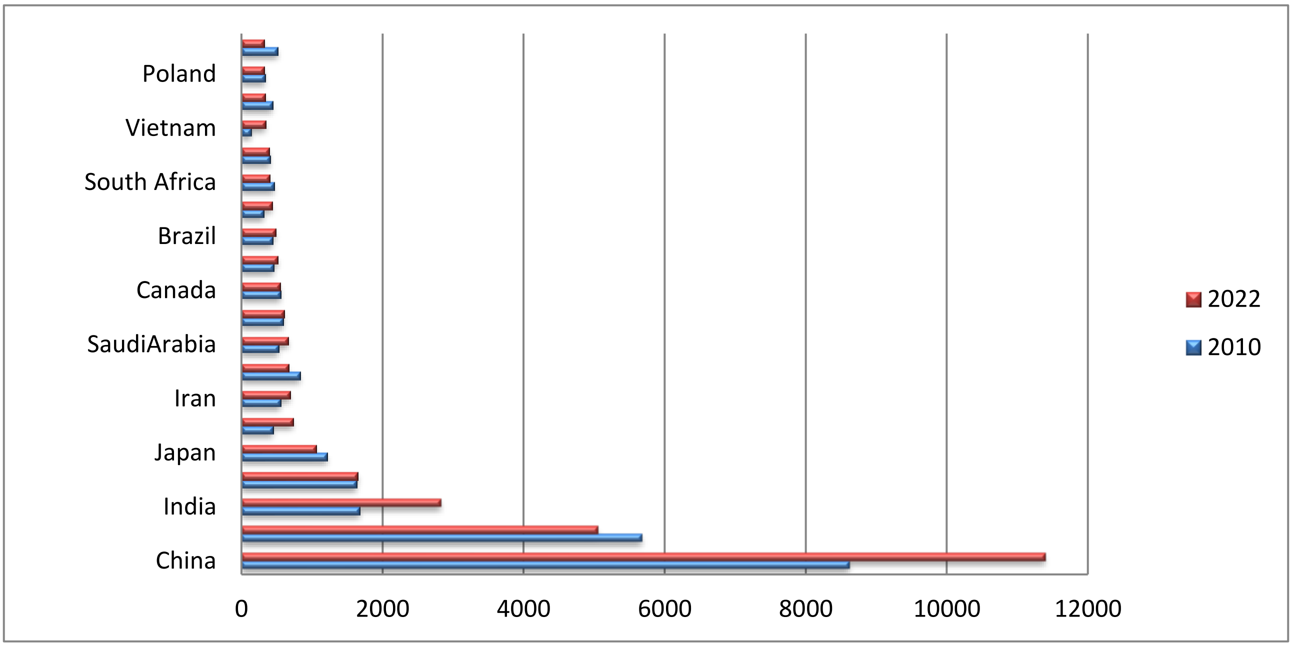
Figure 2: Contribution of Top Polluting Countries in Global Carbon Emissions in 2022



In addition, these top polluted countries are also the top energy consuming countries of the world. According to the British Petroleum Statistics (BP, 2022) these countries account for 80% of total global energy consumption. Unfortunately the fossil fuel energy dominates their energy mix which makes these countries blameworthy for the highest energy based CO_2 emissions globally. Besides these countries have experienced rapid economic growth which led to substantial CO_2 emissions and global warming in these countries from the period 2010 to 2022 as evident in Figure 3. Consequently, climate change and global warming have increased significantly which has posed serious challenges and require careful attention of the researchers (Bhattarai, Maraseni, & Apan, 2022).

Literature has documented several factors responsible for environmental degradation such as financial development, economic growth, foreign direct investment, globalization etc. Likewise, the structural transformation is recently gaining the attention of the researchers for its contribution to environmental degradation. To measure structural transformation, Hidalgo and Hausmann (2009) proposed the economic complexity conditional on the science of complexity. Economic complexity refers to the knowhow, skills, qualities and the structural transformation in an economy. It refers to the knowledge combined, accumulated and transferred in an economy. The effect of economic complexity on environment is like a sword with two faces. On the one hand, the production structure of a country is reflected in its degree of economic complexity which in turn determines the pattern of energy consumption and the environmental quality. Higher production scale might result from a more advanced economic structure, which would raise the demand for traditional energy sources and consequently lead to the degradation of the environmental quality (Doğan et al., 2021). On the other hand, enhanced knowledge and improved economic structure bring advanced technology which enables the countries to use energy resources more efficiently (Adekoya et al., 2023).

Figure 3: CO_2 emissions (million metric tons) in Most Polluted Countries Worldwide in 2010 and 2022



The increased awareness of environmental dangers and the need for global actions have made it clear that incorporation of the green technologies into a variety of growth-dependent industries becomes a beneficial instrument for improving environmental quality (Afshan & Yaqoob, 2021). The concept of green technologies is predicted to reduce waste, material resource consumption and pollution (Sun, Duru, et al., 2021; Yurdakul & Kazan, 2020). Green technologies refer to the innovative concepts for the improvement of the production processes and products while lowering environmental burdens (Ding, Khattak, & Ahmad, 2021; Mensah et al., 2018). Product innovations can assist firms to enhance their quality of the product, while process innovation can help those lower costs. Green product innovation is accomplished by upgrading existing or introducing new products to address environmental problems, whereas green process innovations demand R&D investment to change existing business operations, increasing technology investment and lowering resource costs and greenhouse gas emissions (Fethi & Rahuma, 2020). Green technologies can be a useful tool for implementing a strong environment strategy and boosting operating effectiveness, long-term stability, and environmental practices all of which help in improving the quality of the environment (Jin et al., 2021).

Keeping in view the above discussion, the researchers are interested to answer the two research questions: 1. What is the effect of economic complexity on environmental degradation? 2. What is the effect of green technologies on environmental degradation? To answer these questions, the objective of the study is to examine the impact of green technologies and economic complexity in 13 top polluting countries over 2000 to 2020 period. Based on the previous discussion, the top polluting countries need attention for empirical assessment as the countries have the highest contribution to the global CO_2 emissions as compared to the other countries. In addition these countries hold higher rank in terms of economic complexity as per the economic complexity index rankings. Hence, it is pertinent to consider that these countries are the prominent exporting and the economically complex economies (Zheng et al., 2021). But the empirical assessment of the role of economic complexity and green technologies in environmental degradation in these countries is yet to be done. Therefore, the current study aims at analyzing the impact of economic complexity and green technologies on environmental degradation and adds to the body of the literature significantly. The remaining sections of the study are organized as follows: the review of previous literature is given in section 2. Section 3 gives data and methods of analysis. Section 4 describes results and discussions on them. Section 5 provides conclusion and policy recommendations.

2. Literature Review

This section comprises of two sub sections in which firstly a brief review of the nexus between green technologies and environmental degradation is provided while the latter sub section reviews the corresponding empirical literature related to economic complexity and environmental degradation nexus.

2.1. Green Technologies and Environmental Degradation Relationship

As the world economies prepare to ride the Fourth Industrial Revolution waves, technological innovations are seen as the most effective way of accomplishing the sustainable development goals (SDGs) (Ahmad et al., 2020). Technological advancements in this situation are likely to have an impact on environmental characteristics (Baloch et al., 2021; Murshed, Chadni, & Ferdaus, 2020). More specifically, green technologies are thought to be a solution to the environmental problems all over the world (Ding, Khattak, & Ahmad, 2021; Mensah et al., 2018; Wang et al., 2020). Relationship between green technologies and environmental degradation has been widely studied in the previous studies. For example Sun, Yesilada, et al. (2021) analyzed the effect of globalization and green innovations in carbon emission mitigation in the United States (USA). According to QARDL estimation results, green innovations reduced but globalization increased CO_2 emissions in the USA. Ding, Khattak and Ahmad (2021) analyzed the effect of green innovations on CO_2 emissions in a group of 7 economies over 1990 to 2018 period. The results of AMG and CSARDL analyses suggested that green technologies reduce CO_2 emissions in these countries. Chien, Ananzeh, et al. (2021) studied the role of green innovations in achieving carbon neutrality targets in the USA over 1970 to 2015 period. The findings of QARDL estimation revealed the significant negative effect of green innovations on CO_2 and PM2.5 emissions in the USA. In G-7 countries, Zhao, Liu and Huang (2022) examined the role of green innovations in CO_2 emissions over the 1995 to 2018 period. The findings of CS-ARDL, AMG and CCEMG analyses revealed the positive role of green innovations in CO_2 emissions. Chien, Sadiq, et al. (2021) studied the impact of green innovations on PM2.5 and carbon emissions in top Asian economies. Green innovations had negative impact on PM2.5 and carbon emissions in selected countries.

2.2. Economic Complexity and Environmental Degradation Relationship

This strand of the literature focuses on the nexus between economic complexity and environmental degradation. For instance, Murshed et al. (2022) empirically studied the impact of economic complexity on environmental quality measured by carbon footprints and CO_2 emissions in G-7 economies over 1995 to 2016 period. According to the study findings, economic complexity enhances the quality of the environment in studied economies. Doğan et al. (2021) studied the effect of economic complexity on CO_2 emissions by considering the panel of 28 OECD countries for 1990 to 2014 period. DOLS, FMOLS and AMG estimations showed that economic complexity reduced carbon emissions. For China, Yilanci and Pata (2020) analyzed the effect of economic complexity on ecological footprints over 1965 to 2016 period. According to Fourier ARDL model, economic complexity reduced ecological footprints in China. In case of 118 countries, Chu (2021) evaluated EKC hypothesis in the context of economic complexity over 2002 to 2014 period. GMM estimation was used and the findings revealed that inverted U-shaped nexus was present between CO_2 emissions and economic complexity. Hassan et al. (2023) studied the economic complexity and ecological footprints nexus in the USA over 1985 to 2016. The results of DARDL estimation indicated that economic complexity increased ecological footprints. Likewise, Rafique et al. (2022) studied the role of economic complexity in ecological footprints by taking a panel of top ten economically complex countries over 1980 to 2016 period. According to the findings of the FMOLS, DOLS and GMM estimation techniques, economic complexity increased ecological footprints. Considering a panel of green energy using countries spanning over 1995 to 2020 period, Saqib and Dincă (2024) studied the role of economic complexity in carbon emissions using NARDL approach. Positive shocks in economic complexity were found to reduce, whereas negative shocks were found to increase carbon emissions.

3. Data and Methodology

To empirically estimate the relationship between dependent and independent variables, the IPAT framework proposed by Dietz and Rosa (1997) is considered to build theoretical foundations for model specification. IPAT model considers the environmental quality as a function of three parameters namely income, technology and population. The mathematical expression for IPAT model is given as follows:

$$I = P * A * T \tag{1}$$

Where, I represent environmental quality, A represents affluence, P denotes population and T shows technology. In recent times with further development, the basic IPAT framework is extended into a stochastic version by York and Rosa (2003) named as Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework to analyze the non-proportionate impact of affluence, population and technology on environmental quality (Shan et al., 2021). The basic STIRPAT model can be written as

$$I_i = \alpha P_i^{\beta} A_i^{\gamma} T_i^{\delta} \varepsilon_i \tag{2}$$

And the equation (2) in its logarithmic form can be represented as:

$$logI_i = \alpha + \gamma logA_i + \beta logP_i + \delta logT_i + \varepsilon_i \tag{3}$$

On the basis of the STIRPAT framework, the model of the study is formulated as:

$$CO_{2it} = \beta_0 + \beta_1 ECOMP_{it} + \beta_2 GT_{it} + \beta_3 EG_{it} + \beta_4 EG_{it}^2 + \beta_5 IND_{it} + \beta_6 URB_{it} + \beta_7 ET_{it} + \varepsilon_{it} \tag{4}$$

In equation (4), I component of STIRPAT framework is measured by CO2 emissions, T by green technologies, P by urban population and A by economic growth. Moreover, following the studies of Caglar et al. (2022), Koengkan and Fuinhas (2020) and Li and Lin (2015), economic complexity, industrialization and energy transition are added to formulate the model of the study. Table 1 gives the necessary detail of the variables of the study is given.

Table 1: Operational Definitions of the Variables and their Data Sources

Variables	Measurement	Data Source
Environmental Degradation	CO_2 emissions (metric tons per capita)	WDI
Economic Complexity	Economic complexity index	Observatory of Economic Complexity
Green Technologies	Innovations in environmental related technologies (as percentage of total technologies)	OECD
Economic Growth	GDP constant (2015US$)	WDI
Urbanization	Urban population (% of total population)	WDI
Industrialization	Industrial value added (% of GDP)	WDI
Energy Transition	Ratio of renewable energy to non-renewable energy	EIA

3.1. Methods of Analysis

3.1.1. Cross Sectional Dependence (CSD) Test

CSD refers to the existence of interdependence or correlation among the cross sectional units in a dataset or sample. In other words, CSD exists when the sample observations are dependent on each other. In this regard, Pesaran (2004) CSD test is used in the present study. The basic statistics of the test is given as:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \right) \sim N(0,1)i,j \tag{5}$$

where, $\hat{\rho}_{ij}$ is the pairwise correlation coefficient. The null hypothesis of the test states that CSD does not exist in data and the alternative hypothesis assumes the presence of CSD in panel data.

3.1.2. Unit Root Tests

The cross-sectional augmented Dickey-Fuller tests (CADF) and cross-sectional augmented Im, Pesaran and Shin (IPS) tests for unit root proposed by Pesaran (2007) are applied in the present study. These unit root tests are second generation tests and can effectively handle the CSD problem. The basic equation of CADF test is as follows:

$$\Delta Y_{it} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \bar{X}_{t-1} + \sum_{l=0}^{p} \gamma_i \overline{\Delta Y}_{t-1} + \sum_{l=1}^{p} \gamma_{il} \Delta Y_{i,t-1} + \varepsilon_{it} \tag{6}$$

Where, $Y_{i,t-1}$ and $\Delta Y_{i,t-1}$ denotes the averages of first difference and lag values. The CIPS equation is written by taking the mean of CADF as follows:

$$\widehat{CIPS} = \frac{1}{N} \sum_{i=1}^{n} CADF_i \tag{7}$$

3.1.3. Long Run Estimation using CCEMG Estimator

The CCEMG estimation technique is used to estimate the study model. This estimation approach is a heterogeneous panel data estimator which is capable of addressing the issue of CSD caused by common factors and robust to measurement errors, omitted variable bias, serial correlation, structural breaks and the stationarity properties of the variables (Pesaran, 2006). The CCEMG approach also provides robust estimation in the presence of strong factors such as global shocks as well as in weak factors like local spillover effects (Tenaw & Hawitibo, 2021). The basic CCEMG estimator is given as:

$$y_{it} = a_{1i} + \beta_i x_{it} + \varphi_i f_t + \varepsilon_{it} \tag{5}$$

Where, β_i shows the slope of the independent variables. a_{1i} represents the fixed effects which capture the time invariant heterogeneity among groups. f_t denotes the unobserved common factor and ε_{it} denotes the error term. Equation (5) is augmented with the cross sectional averages of the dependent and independent variables as follows:

$$y_{it} = a_{1i} + \beta_i x_{it} + \delta_i \bar{y}_{it} + \theta_i \bar{x}_{it} + \varphi_i f_t + \varepsilon_{it} \tag{6}$$

For CCEMG estimator, we can calculate the mean group estimator as follows:

$$CCEMG = N^{-1} \sum_{i=1}^{N} \hat{\beta}_i \tag{7}$$

4. Results and Discussions

At the beginning of the empirical analysis, descriptive statistics revealing basic data characteristics including mean, data range and standard deviation are reported in Table 2. The highest mean and standard deviation are reported for economic growth while the values of mean and standard deviation are the lowest for economic complexity among all series. Table 3 gives the correlation matrix which indicates the direction and strength of the association among variables. The correlation matrix indicates that green technologies, industrialization and energy transition are negatively correlated whereas all other variables are positively correlated with CO_2 emissions.

Table 2: Descriptive Statistics

Variables	Mean	Standard Deviation	Minimum value	Maximum value
CO_2	8.794	4.955	1.701	20.469
ECOMP	1.020	0.644	-0.310	2.262
GT	4.066	1.522	0.94	11.02
IND	26.723	6.388	16.99	47.55
GDP	334000	451000	22211	199000
GDP^2	314000	796000	49100	397000
URB	74.402	11.395	35.877	91.782
ET	0.1557	0.1586	-0.0413	0.7000

Table 3: Correlation Matrix

Variables	CO2	ECOMP	GT	IND	EG	URB	ET
CO2	1.000						
ECOMP	0.152	1.000					
GT	-0.062*	-0.016*	1.000				
IND	-0.226	-0.194	-0.171	1.000			
EG	0.398	0.384	-0.336	-0.037**	1.000		
URB	0.333	0.382	0.139	-0.613	0.0643*	1.000	
ET	-0.315	0.112	0.052*	-0.346	0.119	0.401	1.000

The findings of CSD test are given in Table 4. The statistically significant test statistics confirm the presence of CSD among the data series. These statistics imply that any change in an explanatory variable in one of the top polluting countries impact the corresponding variable in at least one of the other countries as well. Consequently, ignoring the CSD issue in data is likely to provide inefficient estimates.

Table 4: Findings of CSD Test

Variables	Statistics	P-value
CO_2	6.862***	0.000
ECOMP	0.059	0.953
GT	1.134	0.257
EG	31.01***	0.000
IND	8.671***	0.000
ET	15.00***	0.000
URB	34.449***	0.000

Where, *** shows significance at 1%

Table 5 presents the results of the CADF and CIPS unit root tests which are appropriate to apply in the presence of CSD issue in panel data. The test statistics from both the CADF and CIPS tests affirm a mixed integration order among the variables taken into consideration for the empirical analysis.

Table 5: CIPS and CADF Tests

Variables	CIPS		CADF	
	level	1st difference	level	First difference
CO_2	-0.992	-3.813***	-1.231	-2.680***
ECOMP	-1.482	-3.645***	-1.766	-2.631***
GT	-2.534***	---------	-2.186*	----------
EG	-1.584	-2.503***	-1.776	-2.503**
IND	-1.932	-3.905***	-2.043	-2.638**
ET	-1.503	-4.102***	-1.256	-2.679**
URB	-1.702	-3.382***	-0.827	-3.382***

Where, *** and ** show significance at 1 and 5%, respectively

The results from the CCEMG panel data regression are shown in Table 6. The estimation shows that economic complexity has statistically significant and positive impact on environmental degradation. This indicates the positive association of economic complexity with economic growth which in turn increases CO_2 emissions by increasing the demand for energy and production scale (Khezri, Heshmati, & Khodaei, 2022). The finding is inline with You, Zhang and Lee (2022) and Huang et al. (2022) who conclude that economic complexity increase CO_2 emissions, but in contradiction to Can and Gozgor (2017) who found that economic complexity reduces CO_2 emissions in France.

Table 6: Findings of CCEMG Estimation

Variables	Coefficients	P-value
ECOMP	0.770**	0.024
GT	-0.126**	0.037
EG	-1.271	0.898
EG^2	6.692	0.579
IND	0.112*	0.053
ET	-13.08**	0.017
URB	-6.720	0.053

Where, ** and * show significance at 5 and 1%, respectively.

In contrast, the results indicate that green technologies have significant and negative impact on environmental degradation, indicating that higher level of green technological innovations in selected economies lead to lower levels of CO_2 emissions in the selected countries. Earlier research studies have also found the same relationship between green technologies and CO2 emissions, such as Hsu et al. (2021) observed the negative association between green technologies and environmental pollution in China. Ahmad et al. (2021) also affirm that green technologies reduce ecological footprints in G-7 economies. Similar findings were given by Chien, Ananzeh, et al. (2021) for the USA and Zeraibi, Balsalobre-Lorente and Murshed (2021) for ASEAN countries.

Likewise, as per the CCEMG estimates, the relationship between energy transition and CO_2 emissions is statistically significant and negative indicating that energy transition reduces environmental degradation in selected countries in line with Koengkan and Fuinhas (2020) who conclude that energy transition mitigates environmental degradation in Latin American and Caribbean countries. Similarly, Yuan et al. (2022) reported that energy transition reduces CO_2 emissions in China. Similar to energy transition, the role of urbanization is also statistically significant and negative in environmental degradation in CCEMG estimation. This outcome is similar to Shahbaz et al. (2016) who report that urbanization reduces CO_2 emissions in Malaysia. Likewise, according to Martínez-Zarzoso and Maruotti (2011), the relationship between urbanization and carbon emissions is negative in upper middle income economies. But the finding is inconsistent with Ali, Bakhsh and Yasin (2019) as they found that urbanization enhances CO_2 emissions in Pakistan. However, the relationship between industrialization and CO_2 emissions is evident to be significant and positive in accordance with the findings of Mentel et al. (2022) indicating that industrialization promotes CO_2 emissions in Sub-Saharan African countries. The study of Salahodjaev et al. (2023) in the context of OIC countries also support the outcomes of the present study by reporting the positive association between industrialization and CO_2 emissions. Last, economic growth and its square do not exhibit any significant impact on CO_2 emissions in the present study.

5. Conclusion and Recommendations

The primary aim of the present study was to empirically analyze the role of economic complexity and green technologies in environmental degradation in top polluting countries. The panel data of 13 countries spanning over 2000 to 2020 period was analyzed using CCEMG estimation technique because of the presence of CSD in data. The findings reveal that green technologies reduce but economic complexity enhances CO_2 emissions in selected countries. Thus the study concludes that economic complexity is detrimental for the environmental quality but green technologies help in improving the environmental quality in selected countries. The findings are robust to various policies for the governments in selected countries. Since economic complexity is detrimental for environmental quality, the government of the selected countries should ensure it that more environmentally friendly technology methods must be used in the production process. In order to reduce carbon emissions, the governments in these countries should increase research and development expenditures on pollution prevention projects. Companies that export advance and sophisticated products should provide tax advantages as well as other subsidies to encourage them to adopt cleaner sources of energy. As a result, the selected countries can increase exports of value added goods and specialized products while also lowering the level of environmental degradation. Furthermore, government actions should include incentives for funding environmentally friendly innovative projects, particularly for developing green technologies that can ensure the balance between economic growth and environmental quality. Although the present research provides valuable insights, it is not without limitations. The main limitation of the present research lies in its scope. The present study selected only 13 top polluting countries for empirically testing the objectives. Future studies can expand the panel by adding more countries as well as disaggregating the countries into developed and developing countries. Second, the study has analyzed the impact of economic complexity and green technologies on environmental degradation only. Future studies can expand this work by studying the effect of product complexity and environmental management technologies on environmental degradation. Moreover, the moderating impact of some pertinent variables such as institutional quality, governance, globalization and economic policy uncertainty must be considered by the future research studies.

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