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Economic complexity and environment degradation: Does income level make a difference?

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Abstract
Purpose: This paper aims to investigate the impact of economic complexity on environmental degradation. Furthermore, this research examines the moderating effect of income on environmental degradation.
Design/methodology/approach: This research collect data of 94 countries spanning from 2010 to 2020. And employed fixed-effects and Generalized Method of Moments (GMM) model to test the relationship between the variables.
Findings: The findings of our study indicate that an increase in economic complexity exacerbates environmental degradation. Additionally, higher income levels are beneficial in mitigating the negative impacts of rising economic complexity on the environment.
Research limitations/implications: This study is limited to macro-level research on multiple country-level data. Future research can conduct more detailed and in-depth enterprise-level research on different regions or a single country.
Practical implications: Understanding how economic complexity and environmental degradation interact and how income levels affect this relationship can help policymakers create more targeted economic and environmental policies for different income levels. Understanding economic complexities can help international cooperation in developing global policies and actions to address environmental degradation in a globalized world. Public awareness of economic complexity, environmental degradation, and their interactions can boost social participation and environmental protection policies. Better education and awareness, especially in high-income areas, can encourage sustainable lifestyles and business practices.
Originality/value: This study enhances empirical research of economic complexity, income, and environmental degradation. It also presents practical empirical evidence that helps us comprehend the real impacts of the relationship between economic complexity and the environment. This facilitates the establishment of a more all-encompassing environmental policy framework and fosters the advancement of sustainable development.

Keywords: economic complexity, income, environmental degradation

Introduction

Climate change is one of the most pressing challenges confronting contemporary society. Since the onset of the Industrial Revolution, global temperatures have risen above pre-industrial levels, presenting significant obstacles to sustainable development (IPCC, 2022). The combination of swift economic expansion, accelerated industrialization, and an expanding population has led to heightened energy requirements, exacerbated environmental deterioration, and posed a threat to the pursuit of sustainable development. Farming, construction, resource extraction, fossil fuel combustion, waste production, and deforestation have all contributed to climate change. These activities increase greenhouse gas emissions, which harm the environment and threaten human life. Everyone is vulnerable to climate change's global effects, making economic growth and environmental conservation crucial. International community faces a huge challenge in achieving this balance. To confront these challenges, countries have ratified international accords pertaining to climate change. The compacts encompass the UNFCCC, the Paris Agreement, and the Kyoto Protocol. Objectives include mitigating carbon dioxide which is the key drivers of global warming.

Economic complexity encapsulates the intricate structural transformations in a country's production processes as it transitions to technology- and knowledge-driven paradigms. This complexity involves factors such as knowledge acquisition, skill development, product diversity, and ubiquity. Recent research highlights the potential interaction between CO_2 emissions and national production structures (Romero & Gramkow, 2021; Wang & Lee, 2022). A nation's production structure mirrors its technological and production capacities, which in turn shape its potential for economic diversification (Hidalgo et al., 2007). On the one hand, transition from agrarian-based systems to industrialization, accompanied by widespread use of fossil fuels and innovative technologies, has had significant impact on the environmental quality (Adedoyin et al., 2020). Conversely, the progressive transition in industrial development towards more modern and environmentally sustainable economic structures characterized by a decrease in polluting heavy industries and an increase in service sector activities might positively influence environmental quality (Apergis et al., 2018). Changes in the structure of a country's economy have a direct impact on the quality of the environment, while the complexity of products may also contribute to environmental pollution (Romero & Gramkow, 2021). For this reason, it is crucial to develop effective policies to fight environmental degradation if we can comprehend how economic complexity affects environmental pollution.

Economic complexity is acknowledged as a comprehensive gauge of a nation's economic advancement, encompassing factors such as knowledge, skills, product diversity, and ubiquity (Hidalgo & Hausmann, 2009). It offers insights into the intricacies of industrial systems, providing a platform for assessing production structures and variations. Significantly, it has demonstrated potential in predicting and explaining variations in economic growth and environment across regions and nations (Hidalgo, 2021). Current scholarly investigations underscore the progressive shift away from agriculturally reliant and pollution-intensive production paradigms towards more advanced, knowledge-centric systems (Mealy & Teytelboym, 2022). This changing viewpoint highlights the connected nature of economic intricacy and environmental deterioration (Abbasi et al., 2021; Majeed et al., 2022). Theoretically, as income and economic growth go up, so do worries about damage to the environment. Since economic complexity is a key factor in explaining and predicting differences in income and growth rates between countries (Hidalgo & Hausmann, 2009;

Hidalgo, 2021), it has important effects on the quality of the environment. But countries are becoming more and more motivated to make new, complex products that require a lot of knowledge to make their products more competitive and keep their economies growing. So, policymakers are thus confronted with the dilemma of whether to propel the economy towards greater complexity. Thus, to further understand how economic complexity influences environmental deterioration, we explore whether this relationship is moderated by income effects. This represents a significant contribution to the exist research, as it introduces a novel perspective.
The structure of the remaining sections of this paper is as follows: the "Literature Review" section delves into previous research in-depth; the "Hypothesis Development" section presents hypotheses about the relationship between the study variables; the "Methodology" section provides details on research methods, model specifications, and estimation strategies. The "Findings" section reports empirical results, and the "Discussion and Conclusion" section summarizes the research results of the paper while providing policy implications.

Literature Review

Economic Complexity (EC) is a concept that measures the diversity and complexity of a country's economy. It is not only about the quantity of goods and services produced, but also about the complexity of these products and the diversity of technology and skills required in the production process. Hidalgo and Hausmann (2009) conceptualise economic complexity (EC) as the existing productive capacity of a country and its interactions. Complexity indicators are effective because they capture information about the structure of production that bypasses simple aggregate indicators and captures information about the complexity of activities implicit in geographical distribution. For example, if exporting cars involves production, design, R&D, supply chain, etc., and is categorised and measured from the low end to the high end, the higher the exported cars, the higher the complexity of the country's economy, while economic complexity also takes into account the 'Jacob's spillover' of economic development, which refers to the 1+1 spillover of knowledge from the synergy of similar industry sectors. At the same time, economic complexity also takes into account the 'Jacob's spillover effect' in economic development, which refers to the effect of 1+1>2 when knowledge from similar industrial sectors is combined. For example, if industries with spillover effects are clustered in one place, they can form a correlation network of different products according to the correlation of their output data, the more basic raw material production is, the more it is at the edge of the network, and the more high-end industries, the more they need to accumulate knowledge (Neagu & Teodoru, 2019).
Economic complexity determines its productivity by considering the activities associated with economic growth and complexity. Although part of the literature demonstrates that EC plays an important role in reducing environmental emissions, EC has economic disadvantages in terms of environmental degradation, such as contributing to the rise in greenhouse gas and carbon emissions. Economic development has empowered countries to invest in renewable energy and financial development, which can help mitigate environmental degradation (Neagu & Teodoru, 2019; Agozie et al., 2022). Similarly, the research by Doğan et al. (2021) on carbon dioxide emissions indicates that economic complexity can facilitate the reduction of emissions through the adoption of innovative technologies associated with renewable energy sources. The transition of economies from extractive industries to more complex sectors necessitate increased energy usage, impacting the carbon footprint levels of these economies. Literature on international trade suggests that EC establishes a high-tech level of industrial output and knowledge-based manufacturing structures, providing crucial evidence of an economy's economic structure and technological level (Can & Gozgor, 2017). Economic complexity

reflects an economy's productive capacity in manufacturing development. The intensity of EC reveals a country's ability to diversify its goods and services, analysing its industrial systems and production structures. It also offers a comprehensive assessment of a nation’s structural, size, and technological changes. Furthermore, EC can predict and elucidate regional and global differences in economic development and greenhouse gas emission processes (Hidalgo, 2021). Moreover, the diversity of products can influence energy consumption and environmental quality (Neagu & Neagu, 2022).

The selection of criteria employed to assess environmental degradation may partly account for the discrepancy in research results. Ahmad et al. (2021) examined 20 emerging nations from 1984 to 2017. Their findings showed that economic complexity was linked to environmental degradation. Romero & Gramkow (2021) used a systematic GMM approach and carbon emissions to indicator environmental deterioration, reaching a different conclusion. Boleti et al. (2021) computed an environmental performance index by amalgamating various environmental indicators and discovered that economic complexity enhances environmental performance but also leads to higher emissions of CO_2, N2O, and CH4, as well as increased exposure to PM2.5. Aluko et al. (2023) sampled OECD countries and found that in fixed-effects models, economic complexity primarily exacerbates environmental degradation through the channel of CO_2, greenhouse gases.

Notable critical theories examining the correlation between economic complexity and environment encompass the EKC hypothesis, the STIRPAT theory, and the pollution paradise hypothesis. The Environmental Kuznets Curve (EKC) theory illustrates a non-linear relationship between economic development and environmental quality. It suggests that as economic levels rise, there may be an initial increase in environmental degradation, followed by an improvement in environmental conditions beyond a certain threshold. STIRPAT theory provides a scientific basis for formulating environmental policies by analysing multiple factors such as population, economic prosperity, and technological level and quantifying their impact on the environment. At the same time, the pollution paradise hypothesis emphasizes that some countries may attract foreign investment by lowering environmental standards, but this may lead to the transfer of environmental problems on a global scale. These theories provide a practical, theoretical framework for in-depth research. This study establishes a basic research framework based on these three theories to investigate the impact of increased economic complexity on environmental quality. Furthermore, in order to make the estimates more comprehensive, we attempted to measure environmental degradation using a variety of indicators.

Hypothesis Development

The essence of the concept of economic complexity is intimately linked with the breadth of knowledge it encompasses. Research indicates that a nation's export capabilities and domestic production are critical to economic growth (Bustos et al., 2012). Generally, the more complex the production structure, the faster the economic growth. Nations with greater capabilities can produce a more diverse array of products, thereby increasing product diversity (Hidalgo & Hausmann, 2009). Thus, an increase in economic complexity leads to scale effects (Abdon et al., n.d.). Some studies support the view that a more complex economic structure fosters broader development, demonstrating a positive correlation between a higher Economic Complexity Index (ECI) and faster economic growth (Koch, 2021; Lee & Lee, 2019). However, while economic complexity contributes to economic growth and can serve as an indicator of development, the increased scale effects may also bring about environmental pollution as a side effect. As more scholars investigate this complex relationship, inconsistencies emerge in the findings. Factors such as sample selection, model specifications,

measurements of environmental degradation, and econometric methods can influence the conclusions. Thus, we propose the following hypothesis:
Hypothesis 1: Economic complexity has a significantly positive effect on environmental degradation.

Moreover, our research aims to investigate the moderating role of income, recognizing the vital significance of income factors in discussions about environmental degradation and economic complexity. In our investigation of EC on environmental degradation, the selection of income as a moderating variable primarily arises from the following considerations: Firstly, environmental degradation may vary with income levels. As economic complexity increases, environmental degradation may exacerbate at lower income levels but attenuate at higher income levels. EKC hypothesis posits that as income rises, there is an initial increase in environmental degradation, followed by a subsequent improvement at higher income levels (Dinda, 2004; Adedoyin et al., 2021). Secondly, the Pollution Haven Hypothesis underscores the influence of income on environmental outcomes, suggesting that disparities in production factors are predominantly linked to a nation's wealth, with developing countries offering lax environmental regulations that encourage pollution-intensive industries from higher-income nations to relocate there (Zhang & Zhou, 2016; Shahbaz et al., 2018).
As discretionary income increases, strategies to mitigate the environmental impact of economic complexity may emerge. Rising incomes may first increase ecological awareness and prioritize environmental issues. With higher income, people and societies may be more inclined to invest in environmental protection and adopt environmentally friendly technologies. This trend promotes sustainable production and consumption. High-income countries have greater power to formulate and implement environmental policies and advance environmental rules. In addition, higher incomes may change purchasing patterns, encourage people to purchase environmentally friendly and sustainable products and promote environmental education and awareness. Therefor, income may be an important factor in balancing economic complexity with environmental sustainability. Thus, we propose the following hypothesis:
Hypothesis 2: Income has significant negative moderating effect on economic complexity to environmental degradation.

The study collected data from a wide range of 94 countries. A comprehensive study analysed the impact of economic complexity on the environment employing fixed-effect model and GMM model. Numerous studies have utilized income stratification to conduct heterogeneity analysis, highlighting how different income levels impact this relationship. However, the effectiveness of wealth as a moderating variable in the global analysis of the relationship between economic complexity and environmental degradation still warrants further exploration. Introducing income as an interaction term in the relationship between EC and the environment offers significant insights into its role as a global determinant. This approach not only helps to unravel the complexities of how economic structures and environmental outcomes are intertwined but also elucidate disparities in environmental impacts and economic growth patterns. It is crucial to analyse how income levels modify the effects of EC on environmental degradation, as this could lead to more tailored and effective policy interventions that address both economic development and environmental sustainability. Observing income in this context provides a clearer perspective on the potential for sustainable economic practices globally.

Methodology

Regression Model

The empirical model is based on the theoretical foundations of the EKC, the STIRPAT model, and the pollution haven hypothesis (PHH). The Environmental Kuznets Curve posits a theoretical connection between the path of economic growth and the deterioration of the environment. The STIRPAT model contain population size, income level, and technological advancement as the primary factors that contribute to environmental degradation. Concurrently, the Pollution Haven hypothesis posits that as national borders become more permeable to global economic forces, certain nations tend to emerge as potential refuges for enterprises engaged in pollution-intensive production activities. Upon a cursory exposition of these theoretical frameworks, it is evident that Gross Domestic Product (GDP), income, population size, technological sophistication, and trade openness constitute pivotal factors underlying environmental degradation. Consequently, environmental degradation can be characterized as a multifaceted function influenced by the interplay of these variables. We formally specify the empirical model as follows:

$$ED = f(EKC, STIRPAT, OPENNESS) \quad (1)$$

In this context, EKC represents the Environmental Kuznets Curve, primarily tested using GDP and its quadratic term. STIRPAT model incorporates factors such as population, income, and technology, measured respectively by population size, income per capital, and patent application data. Openness denotes the degree of market openness, typically represented by Foreign Direct Investment (FDI). Therefore, the environmental degradation function can be extended as follows：

$$ED_{it} = \alpha + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 POP_{it} + \beta_4 TEC_{it} + \beta_5 FDI_{it} + \beta_6 INC_{it} + \varepsilon_{it} \quad (2)$$

where ED, GDP, GDP^2, POP, TEC,FDI, and INC represent environmental degradation, GDP per capital, squared of GDP per capital, total population, number of patent technology applications, foreign direct investment, and income respectively. ε is the error term. Considering the objectives of this study, and following the consideration of the primary research variable, economic complexity's impact on the environment, the core variable of Economic Complexity Index (ECI) has been incorporated to assess its influence on environmental degradation. The final environmental degradation estimation model is presented as follows:

$$ED_{it} = \alpha + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 POP_{it} + \beta_4 TEC_{it} + \beta_5 FDI_{it} + \beta_6 INC_{it} + \beta_7 ECI_{it} + \varepsilon_{it} \quad (3)$$

In order to test the effect of income on EC to environmental degradation, we included interaction factors in Equation (3). The model is extended as follows:

$$ED_{it} = \alpha + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 POP_{it} + \beta_4 TEC_{it} + \beta_5 FDI_{it} + \beta_6 INC_{it} + \beta_7 ECI_{it} + \beta_8 ECI_{it} * INC_{it} + \varepsilon_{it} \quad (4)$$

To research the relationship between ECI and environmental degradation, summary statistics, correlation analysis and VIF tests were conducted to avoid multicollinearity. Data was initially

analysed using a panel data method, static model and the fixed effects model. However, the possible endogeneity between variables cannot be effectively addressed (Adedoyin et al., 2021). Therefore, the dynamic GMM model was used to assess serial correlation and control for heteroscedasticity and endogeneity in the dependent variables. When the dependent variable is dependent on prior realizations, this model becomes very important, underscoring the significance of dynamic model estimation (Arellano & Bond, 1991).
Considering the specific effects and simultaneous bias, the GMM estimator uses first-order differencing with lagged regression variables to transform the equation, following the framework outlined by Arellano and Bover (1995). The Difference GMM estimator can be misleading, though, if the explanatory variables don't go away and the lag levels aren't very good (Arellano & Bover, 1995). System GMM combines the level equation and the difference equation to perform first-order differencing GMM model (Blundell & Bond, 1998). The consistency of GMM estimators heavily relies on passing key diagnostic tests. Hansen test checks the validity of the instruments, where a failure to reject the null hypothesis suggests that the instruments are appropriate and the model is well-specified. Additionally, the serial correlation test examines the residuals of the differenced equation for first and second-order serial correlations. A model that correctly rejects the first-order serial correlation AR(1) but does not reject the second-order serial correlation AR(2) is likely well-specified, as indicated by the findings in (Ibrahim & Law, 2014). In our analysis using Equation (4), we employed the System GMM estimator and conducted these essential tests to ensure the robustness of our findings.

Data

This research sampled 94 countries from 2010-2021 based on data availability (see Table 1A). Following Adedoyin et al. (2021) and Aluko et al. (2023), this study use multiple proxy variables to represent environmental degradation. Although carbon dioxide is the principal gas driving global warming, the Intergovernmental Panel on Climate Change noted that it has been surpassed. Thus, we evaluate carbon dioxide emissions, greenhouse gas emissions, and ecological footprint as the measurement of environmental degradation. Economic Complexity Index (ECI) also measures economic complexity as an index number. Table 1 shows definition and sources of dependent and independent variable.

Table1. Data Sources

Variables	Definition	Sources
CO_2	Carbon emissions (kt)	World Bank
EFP	Ecological footprint (Number of earths)	
GHG	Total greenhouse gas emissions (kt of CO_2 equivalent)	
GDP	GDP per capital (current US$)	
FDI	Foreign direct investment, net inflows (% of GDP)	
POP	total population	
INC	Adjusted net national income per capital (current US$)	
TEC	Technology complexity	OEC, World
ECI	Economic complexity index	OEC, World

Note: Except for ECI, TEC and FDI indicators, all data are subjected to regression models using natural logarithm transformed data.

The ECI is an indicator used to measure EC. The index is based on the explicit comparative advantage of a country's exports, and uses a reflexive methodology to derive an indicator of the EC of each country, taking into account the diversity and universality of its exports. This index is calculated based on data from the United Nations Commission on Trade in Goods, the International Monetary Fund and the World Development Indicators. The higher the ECI value, the higher the capacity of a country in the production process (Aluko et al., 2022). GDP per capital, population, income, technology, and openness are other independent variables. GDP per capital is measured in current US dollars, and population is based on the World Development Indicators' total population. Income per capital data obtained from WDI is also measured in US dollars to match GDP standards. To comprehensively consider technological world database (Stojkoski et al., 2023). Openness is reflected net inflow of foreign direct investment as a percentage of GDP, sourced from World bank database.

This study commences with a descriptive and correlational analysis before proceeding to panel data estimation. Table 2 provides a descriptive analysis of the raw data along with their correlations. Prior to estimation, the presence of multicollinearity, which can lead to misleading conclusions and potentially inflate the standard errors of regression coefficients, needs to be examined through multicollinearity tests.

Table 2 Summary statistics and Correlations

	CO_2	GHG	EFP	GDP	POP	INC	TEC	FDI	ECI
Mean	319742.4	427147.2	2.05340	17038.01	$6.83*10^7$	515.5174	4.155604	44.68625	3.172239
Std. Dev.	1160586	1401439	1.26688	20694.04	$1.98*10^8$	297.7669	0.863310	7.614507	0.967538
Min	1003.665	7561.591	0.358454	334.0216	2048583	1.0000	0.992347	0.913654	0.638634
Max	$1.09*10^7$	$1.29*10^7$	5.581991	102913.5	$1.41*10^9$	1031	5.598823	147.5942	5.224719
CO_2	1.000								
GHG	0.998	1.000							
EFP	0.162	0.151	1.000						
GDP	0.072	0.061	0.806	1.000					
POP	0.796	0.819	-0.088	-0.092	1.000				
INC	0.104	0.101	0.060	0.133	-0.008	1.000			
TEC	0.225	0.226	0.534	0.576	0.142	0.126	1.000		
FDI	-0.054	-0.058	0.035	0.056	-0.065	0.000	0.017	1.000	
ECI	0.216	0.206	0.712	0.712	0.076	0.076	0.655	0.034	1.000

To detect multicollinearity, we used the VIF test. According to Miles (2014), a widely accepted guideline in VIF testing is that VIF values should not surpass 10, while tolerance values should not dip below 0.1 in order to ascertain the absence of significant multicollinearity concerns. We set the cutoff for the variance inflation factor (VIF) at 5, as suggested by (Studenmund, 2011). As demonstrated by the VIF test, the VIF values are less than 5 and the tolerance values exceed 0.1 (as shown in Table 3). These results support the conclusion that the inclusion of independent variables in the regression model does not introduce multicollinearity.

Table 3 VIF test

Variable	VIF	$\sqrt{VIF}$	Tolerance	R2
ECI	2.52	1.587	0.397	0.603
GDP	2.27	1.603	0.440	0.560
TEC	1.9	1.378	0.527	0.473
POP	1.09	1.044	0.919	0.081

INC	1.03	1.015	0.975	0.025
FDI	1.01	1.005	0.993	0.007
Mean VIF	1.63			

Findings

Result of Fixed-effects model

In this section, we analyse and present the results of this research. To commence our discourse, we shall present the outcomes of the estimation of fixed-effects models. Table 4 provides a direct analysis of the environmental impact of ECI, and table 5 investigates the moderating effect of INC. The dependent variables in all three models are carbon emissions, greenhouse gas emissions, and ecological footprint.

Table 4 Estimation results of fixed effects model

		Dependent variable (Environmental degradation)	
	CO_2	GHG	EFP
GDP	0.956***	0.336***	0.386***
	[5.66]	[3.39]	[3.47]
GDP2	-0.042***	-0.012**	-0.015**
	[-4.26]	[-2.10]	[-2.28]
POP	1.249***	0.849***	0.121
	[19.19]	[22.25]	[-2.83]
TEC	-0.004	0.001	0.008
	[-0.35]	[0.07]	[1.19]
FDI	0.001*	0.001**	0.001**
	[1.68]	[2.30]	[2.02]
INC	0.013**	0.007**	0.003
	[2.39]	[2.30]	[0.78]
ECI	-0.023	0.031**	0.050***
	[-1.00]	[2.30]	[3.32]

Figures in "[]" stand for t-statistic. * Significance at the 10% level; **Significance at the 5% level; ***Significance at the 1% level

In Table 4, the results indicate that the coefficient for economic complexity in all estimation models is negative when CO_2 is the dependent variable but not statistically significant. However, ECI has positive effects on greenhouse gas emissions and ecological footprints (at the 1%-5% level). This implies that, holding all other conditions constant, an increase in EC in countries within our sample is associated with exacerbated environmental degradation through increased greenhouse gas and ecological footprint. Specifically, with a one-unit increase in economic complexity, it is estimated that greenhouse gas emissions and ecological footprint will increase by approximately 1.03 and 1.05 units on average, respectively. The findings imply that environmental degradation accelerates as countries adopt more complex production structures. The rise in emissions is likely attributable to the increased economic activity that accompanies a more complex trading and production system. This result agrees with the findings of Abbasi et al. (2021) and Boleti et al. (2021).

Table 5 Fixed-effects model with interaction term estimation results

	Dependent variable (Environmental degradation)		
	CO_2	GHG	EFP
GDP	0.935***	0.326***	0.363***
	[5.53]	[3.29]	[3.26]
GDP2	-0.042***	-0.012**	-0.014**
	[-4.19]	[-2.05]	[-2.17]
POP	1.253***	0.851***	-0.116
	[19.26]	[22.29]	[-2.71]
TEC	-0.004	0.001	0.009
	[-0.33]	[0.08]	[1.23]
FDI	0.001*	0.001**	0.001**
	[1.66]	[2.28]	[2.00]
INC	0.040**	0.019*	0.034***
	[2.32]	[1.87]	[2.97]
ECI	0.057	0.065**	0.141***
	[1.07]	[2.09]	[4.03]
ECI*INC	-0.026*	-0.011	-0.029***
	[-1.66]	[-1.21]	[-2.87]

Figures in "[]" stand for t-statistic. * Significance at the 10% level; **Significance at the 5% level; ***Significance at the 1% level

Table 4 indicates a positive effect between INC and environmental degradation, suggesting that increases in income lead to greater environmental stress. Moreover, all measured variables show significant correlations with carbon emissions. In contrast, the interaction between economic complexity and income variables exhibits statistical significance at the 1%-5% level, with a negative coefficient (as shown in Table 5). Carbon emissions and ecological footprints are significantly influenced by the interaction term between ECI and income level, which has a negative coefficient. This indicates that the adverse effects of ECI on environmental degradation can be mitigated by increasing income levels, suggesting that income and economic complexity have substitutive effects in their relationship with environmental degradation.

Although economic complexity worsens environmental degradation, the effects of economic complexity can be mitigated by increasing income, according to the research. In situations where income levels rise, high-income countries are better equipped to invest in research and the application of clean technologies, as well as to focus on efficient resource management and utilization. These countries typically possess more advanced technological and managerial capabilities, enabling them to monitor and manage environmental impacts more effectively, leading to reduced pollution and resource wastage. Furthermore, with rising incomes, there is often an increase in public awareness regarding environmental conservation and ecological balance. This place added pressure on governments to ensure that economic transformation aligns with environmental protection objectives. However, for low-income countries, this balance has not yet been reached yet.

In the analysis of other variables presented, we find that the coefficient for foreign direct investment (FDI) is positive and statistically significant at the 1% level. This association suggests that, with other factors held constant, the net inflows of FDI in the countries studied contribute to a decline in environmental quality, supporting the pollution haven hypothesis. Furthermore, income levels are positively correlated with environmental degradation across all measured variables, underscoring that higher income intensifies environmental harm.
Regarding technological development, the analysis reveals that its impact on environmental degradation is not statistically significant for any of the dependent variables. This indicates that technological progress, in its current state within the sample, does not significantly alleviate environmental degradation. The population variable shows a positive and significant correlation with environmental degradation when carbon dioxide and greenhouse gas emissions are the dependent variables, suggesting that population growth predominantly impacts the environment through these emissions.
Additionally, the analysis provides evidence supporting the EKC hypothesis. The coefficients for the quadratic term of GDP squared are significant negative, indicating an inverted U-shaped relationship between economic growth and environmental degradation. This means that beyond a certain level of economic development, further growth could lead to environmental improvements.

Result of Generalized Method of Moments model

However, results from the fixed-effects models above may suffer from bias due to endogeneity. To address this, the study applies the GMM technique for robustness checks, addressing potential correlations between lagged dependent variables and error terms, as well as the endogeneity problem. Table 6 reports the GMM estimation results for Equation 3, including the two-step difference and two-step system estimators. In theory, two-step estimators are more efficient than one-step estimators as they employ an optimal weighting matrix (Ibrahim & Law, 2014).

Table 6 Estimation results of GMM model

	DV=CO_2		DV=GHG		DV=EFP	
	D-GMM	S-GMM	D-GMM	S-GMM	D-GMM	S-GMM
DV_{t-1}	0.618***	0.974***	0.637***	0.974***	0.198***	0.937***
	[11.94]	[96.71]	[23.07]	[47.47]	[5.83]	[60.44]
GDP	1.001***	0.128**	0.433***	0.268**	0.802***	0.139***
	[5.70]	[2.03]	[8.13]	[2.40]	[8.94]	[3.95]
GDP^2	-0.036***	-0.009***	-0.021***	-0.019***	-0.003***	-0.008***
	[-3.75]	[-2.75]	[-6.89]	[-3.14]	[-5.99]	[-4.06]
POP	0.627***	0.015	0.750***	0.010	-0.037	0.008*
	[3.56]	[1.24]	[12.90]	[0.46]	[-0.73]	[1.82]
TEC	-0.018**	-0.028***	-0.010***	0.005*	0.039***	0.029***
	[-2.26]	[-3.13]	[-6.12]	[2.53]	[9.67]	[2.93]
FDI	0.003**	0.001**	0.001***	0.003***	0.001***	0.001*
	[2.51]	[2.27]	[4.18]	[2.89]	[3.53]	[1.81]
INC	0.010	0.021***	0.003***	0.014	0.004***	0.001
	[1.39]	[3.01]	[4.68]	[1.36]	[3.04]	[0.01]

ECI	-0.002	0.053***	0.016**	0.064**	0.027**	0.020***
	[-0.64]	[4.89]	[2.44]	[2.25]	[1.98]	[3.41]
Model criteria						
Hansen	0.218	0.201	0.347	0.268	0.388	0.157
AR (1)	0.000	0.000	0.000	0.000	0.001	0.001
AR (2)	0.150	0.143	0.681	0.516	0.287	0.186
Num. of inst.	60	64	87	41	87	60
Num. of group	94	94	94	94	94	94

Figures in "[]" stand for t-statistic. * Significance at the 10% level; **Significance at the 5% level; ***Significance at the 1% level; D-GMM represents different-GMM model; S-GMM represents system-GMM model

Table 6 shows that ECI has a significant positive effective on ED. In other words, a 1% increase in the ECI increases CO_2 by 5.3%, greenhouse gas emissions by 6.4%, and ecological footprint by 2%. In estimation models, INN also has a significant positive effect on ED, especially when carbon emissions are the dependent variable. Thus, income or economic activity increases environmental pressure, worsening environmental degradation. The results indicate that, holding other factors constant, a 1% increase in INN, CO_2 emissions will increase 2.1%. Rising income levels engender heightened economic activity, thereby stimulating augmented demand, production, and consumption. Such heightened economic activities correspondingly amplify the utilization of energy resources, with a pronounced emphasis on fossil fuels. Furthermore, the escalation in production and consumption patterns is concomitant with an upsurge in resource extraction endeavours. The STIRPAT model states that affluence degrades the environment (York et al., 2003), and the income variable supports this. Our findings support previous research by Leitão et al. (2021) and Opoku et al. (2022).

Table 7 GMM model with interaction term estimation results (Two-steps GMM)

	DV=CO_2		DV=GHG		DV=EFP	
	(a)	(b)	(a)	(b)	(a)	(b)
DV_{t-1}	0.974***	0.973***	0.974***	0.974***	0.937***	0.928***
	[96.71]	[226.48]	[47.47]	[154.46]	[60.44]	[114.26]
GDP	0.128**	0.194***	0.268**	0.150***	0.139***	0.141***
	[2.03]	[7.48]	[2.40]	[3.82]	[3.95]	[4.97]
GDP^2	-0.009***	-0.009***	-0.019***	-0.064***	-0.008***	-0.006***
	[-2.75]	[-7.26]	[-3.14]	[-3.11]	[-4.06]	[-3.78]
POP	0.015	0.030***	0.010	0.037***	0.008*	-0.001
	[1.24]	[5.79]	[0.46]	[5.42]	[1.82]	[-0.19]
TEC	-0.028***	-0.015***	0.005**	0.025***	0.029***	0.015***
	[-3.13]	[-7.36]	[2.53]	[-8.66]	[2.93]	[5.28]
FDI	0.001**	0.003***	0.003***	0.001***	0.001*	0.001**
	[2.27]	[5.81]	[2.89]	[2.89]	[1.81]	[2.30]
INC	0.021***	0.048***	0.014	0.046***	0.001	0.013*
	[3.01]	[11.19]	[1.36]	[5.50]	[0.01]	[1.67]

ECI	0.053***	0.077***	0.064**	0.049***	0.020***	0.028*
	[4.89]	[7.42]	[2.25]	[3.28]	[3.41]	[1.82]
ECI*INC		-0.542***		-0.044***		-0.023***
		[-11.96]		[-5.23]		[-2.77]
Model criteria						
Hansen	0.201	0.143	0.268	0.472	0.157	0.102
AR (1)	0.000	0.000	0.000	0.000	0.001	0.001
AR (2)	0.143	0.155	0.516	0.449	0.186	0.208
Num. of inst.	64	93	41	82	60	85
Num. of group	94	94	94	94	94	94

Figures in "[]" stand for t-statistic. Line (a) without interaction and line (b) with interaction. *Significance at the 10% level; **Significance at the 5% level; ***Significance at the 1% level.

Table 7 adds the interaction of ECI and INN. In the GMM model, the coefficient of ECI and INN consistently shows a negative and statistically significant relationship at the 1% level for all measures of environmental degradation. This shows that economic complexity and income increase together to reduce environmental degradation pressures. Income increases mitigate the environmental damage caused by economic complexity. Income and economic complexity index show a clear substitutive relationship.

Regarding the technological variables, consistent with the results in Tables 4 and 5 but more pronounced in Tables 6 and 7, we find that technology leads to a significant reduction in carbon dioxide emissions. However, it increases greenhouse gas emissions and ecological footprint. Ideally, improved technology is expected to enhance environmental sustainability, especially if the technology is dedicated to the production or consumption of renewable energy. Nevertheless, unsustainable technologies may increase energy consumption, such as the production of chemical products, the invention of radioactive materials, etc., which could become drivers of increased emissions as technology advances. It is worth noting that our research findings may be influenced by the measurement of technological use (total patent applications), as it does not inform us about the specific technologies involved.

The coefficient for the FDI variable is positive in both models and statistically significant at the 1% level, as shown in Tables 6 and 7. This suggests that, holding other factors constant, an increase in foreign direct investment will lead CO_2 emission, GHG, and ecological footprint increase (see Tables 6 and 7). FDI has significant effect on environmental degradation. Trade expansion often involves the consumption of energy and resources, and the stricter environmental regulations in developed countries may incentivize polluting industries to relocate to less regulated developing nations (Kisswani & Zaitouni, 2021; Shahbaz et al., 2018, 2019). Thus, international trade can lead to increased energy and natural resource consumption, thereby raising emissions and contributing to environmental deterioration. This could be a driving factor in the results.

The population variable exhibits a significant impact only on the increase in the ecological footprint (Table 6), with no significant influence on carbon or greenhouse gas emissions. In Table 7, population growth significantly increases carbon and greenhouse gas emissions, but it does not have a significant effect on the ecological footprint. Although population growth is associated with economic activity, energy consumption, and resource utilization (Martínez-Zarzoso et al., 2007), the number of countries experiencing declining populations has been on the rise from 2010 to 2019. At least 27 countries or regions have lost at least 1% of their population since 2010 (United Nations, 2019). Consequently, in certain nations, the environmental consequences of population growth may be minimal or even diminishing, owing to limited or declining population growth rates.

Discussion and Conclusion

This study analysed a comprehensive dataset spanning from 2010 to 2020, encompassing data from 94 countries and assessed environmental conditions using a variety of indicators, including CO_2 emissions, total greenhouse gas emissions, and ecological footprints. Analysis through the fixed-effects model yielded robust evidence of a positive relationship between increased economic complexity and greater environmental degradation, corroborating the findings of Adedoyin et al. (2021). Considering the potential endogeneity concerns within the fixed-effects model and enhance the credibility of our conclusions, we adopted the GMM model. The dynamic model analysis reinforced our initial findings, confirming that heightened economic complexity exacerbates environmental impacts. Additionally, our results indicated that higher income could mitigate the effects of economic complexity on the environment, with this moderating effect being statistically significant across all analysed dependent variables.

Considering the widespread impact of climate change and the global race to achieve sustainable development goals, environmental sustainability has become a top priority for developed nations. The results emphasize that the overall increase in existing economic complexity is not environmentally friendly. Economic complexity often accompanies increased resource consumption, waste emissions, and environmental pressure (Neagu & Teodoru, 2019). Regarding the intersection of economic complexity and income that inhibits environmental degradation, a possible explanation is economic complexity and income may stimulate technological innovation and more effective environmental management practices. Combined, a synergistic effect is possible so that economic development no longer means inevitable ecological degradation. New technologies and management methods may improve resource efficiency, reduce emissions, and drive the transition to cleaner and more sustainable production methods. Governments may be more able and willing to formulate and implement environmental policies in times of economic complexity and income levels. This may include enacting stricter environmental regulations, raising emission standards, promoting the use of renewable energy, etc. Therefore, when the cross-terms of economic complexity and income exist, strengthening environmental policies will positively impact environmental degradation.

Given the important role of income, policymakers can redistribute income through public spending, especially through improvements in education and health services, to increase support for low-income groups. This will not only reduce poverty, but also increase awareness and capacity for environmental protection by raising the educational level of society as a whole. At the same time, financial incentives, such as tax breaks, subsidies or financial incentives, are provided to businesses and individuals that use environmentally friendly technologies and practices. These incentives can encourage more businesses and consumers to adopt more environmentally friendly behaviours. The results of this study are similar to those of Aluko et al. (2023) study of OECD countries.

Therefore, we recommend that governments strengthen environmental regulations, particularly in regions characterized by high carbon emissions, to restrict corporate carbon emissions and encourage the adoption of environmentally friendly technologies and production methods. The introduction of environment-related tax policies, such as carbon taxes, can to some extent curb high carbon-emitting behaviours, motivating businesses, and individuals to place greater emphasis on environmental conservation. Such policies can have a more pronounced impact in regions with higher income levels. Developed countries should continue to invest in the use and development of clean energy to alleviate the environmental pressures associated with the growth of economic complexity. In regions experiencing severe environmental degradation, governments may consider measures to incentivize individuals and businesses to allocate a portion of their income dividends toward environmental and sustainable development initiatives. This can be achieved through the provision of tax incentives or subsidies.

Theoretical Implications

This study has many theoretical implications for understanding economic complexity and environmental degradation. First, it extends research on economic complexity and environmental degradation by showing a positive correlation. Secondly, the study also emphasises the importance of income levels in mitigating the environmental impacts of economic complexity and promoting sustainability through income-related policies and strategies. The results challenge conventional wisdom by showing that economic complexity improves environmental quality in industrialised areas, emphasising the importance of industrial context when assessing environmental impacts. Finally, the study recommends strengthening regulation, introducing environmental taxation, and encouraging clean energy investment to improve environmental sustainability. The study's theoretical insights inform these recommendations for governments and policymakers to balance economic growth and environmental protection for sustainable development.

Practical and Social Implications

This study has practical and social implications with real-world relevance. The study recommends strict environmental policies, especially in high-carbon regions. Governments should limit corporate carbon emissions and encourage green technologies and production. To encourage businesses and individuals to conserve the environment, carbon taxes should be implemented, especially in high-income areas. Continued investment in clean energy supports global efforts to reduce economic complexity-related environmental pressures. Socially, the study emphasises public awareness and education. Raising awareness of economic complexity's environmental impacts helps individuals and businesses make informed decisions. In regions with severe environmental degradation, governments may consider tax incentives or subsidies to encourage individuals and businesses to donate a portion of their income dividends to environmental and sustainable development. The study also emphasises global cooperation to address environmental issues by sharing best practises, technologies, and policies for sustainable economic growth and environmental protection.

In conclusion, these implications offer governments and societies a comprehensive roadmap for navigating the complex relationship between economic complexity and environmental degradation, including practical strategies for sustainability and environmental stewardship.

Limitations and Suggestions for Future Research

As is common in empirical research, our research is not without limitations. This study is limited to macro-level research on multiple country-level data. Future research can conduct more detailed and in-depth enterprise-level research on different regions or a single country. The results of our study may be affected by the measurement of the variables and the way of estimate. We attempted to fulfil this requirement as much as possible by using three different indicators of environmental degradation and a range of estimation methods. Future research may revisit the issues discussed in this paper using other proxies and estimation methods.

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