ISSN: 2710-0170

An Empirical Analysis of the Inverted-U Shape Relationship Between Globalization and Environmental Degradation: Based on Environmental Kuznets Curve

Yuheng Sun

Faculty of Social Science and Law, University of Bristol, Bristol, UK

Abstract

This study aims to fill the gaps in existing research on the relationship between environmental degradation and globalization by analyzing panel data collected from 130 countries between 1996 and 2021. Based on the Environmental Kuznets Curve (EKC) framework, the analysis explores whether globalization initially causes environmental harm but turns to improve it after a certain threshold. Both baseline results and robustness checks indicate a significant inverted U-shaped relationship. However, by examining regional heterogeneity, this study finds differences in coefficients and significance levels across continents. This study further examines the moderating role of human capital and finds out that higher levels of education and skills enhance a country's ability to benefit from globalization, thereby altering the turning point and slope of the curve. This study also offers useful policy implications for stakeholders, demonstrating that the environmental effects of globalization are not automatic but conditional.

Keywords

Globalization, Environmental Degradation, Weighted Entropy Method, Human Capital, EKC Hypothesis.

1. Introduction

1.1. Research Background

In the past few decades, globalization has become a defining feature of the world economy that reshapes production systems, capital flows, international investments and even cultural exchange. With the increasing flow of capital, goods, services and information that flows across national borders, the consequences of globalization have become a subject that draws intense attention from both scholars and policymakers.

While globalization has undeniably stimulated economic growth, facilitated the spread of technology and enhanced the connectivity among nations, how it could affect the environment remains complex and controversial. On the one hand, some scholars argue that globalization may amplify environmental degradation. The expansion of trade and the increasing need for industrial products tends to increase energy, resource consumption and carbon emissions, especially in countries pursuing economic growth that relies on export of natural resources. This can result in heavy pollution and severe deforestation, particularly in countries where environmental regulations are weak or poorly enforced, as the supporters of Pollution Haven Hypothesis (PHH) suggests, that globalization may incentivize pollutive industries to relocate to countries with lax environmental standards, further exacerbating global environmental inequalities[1] (Cole, 2004). On the other hand, globalization can also promote environmental improvement through various mechanisms. The "technique effect" points out that increased openness facilitates technology transfer, including cleaner production techniques and systems that improve energy consumption efficiency. In addition, globalization can expose domestic firms to global competition and environmental regulations, pushing them toward greener technology transformation and sustainability innovation[2] (Antweiler et al., 2001). Through cultural and informational exchange, globalization also fosters environmental awareness, which can enhance environmental governance.

Overall, the complexity of the globalization–environment relationship has led scholars to explore the possibility of a non-linear relationship. According to the Environmental Kuznets Curve (EKC) hypothesis, environmental degradation initially rises with income level but begins to decline after reaching a certain threshold, forming an inverted U-shape curve. However, empirical evidence on the EKC in the context of globalization remains mixed and needs to be further tested.

Given the rising urgency of preventing environmental degradation, understanding how globalization shapes the environmental performance is not only academically but also practically significant. This study aims to empirically examining the relationship between globalization and environmental degradation, while exploring potential moderating effect caused by human capital at the same time. Moreover, little attention has been paid to regional heterogeneity in this research area. To address this gap, this study also investigates whether the inverted U-shaped phenomenon is cross-regional by analyzing the possible heterogeneity that could appeared in the model.

1.2. Research Significance

1.2.1. Theoretical Significance

From a theoretical perspective, this study introduces a nonlinear perspective based on the Environmental Kuznets Curve framework, contributing to the evolving research on the relationship between globalization and the environment. While the EKC has traditionally been applied to study the relationship between income level and environmental degradation, this study extends its application by testing whether similar dynamics apply to the relationship between globalization levels and environmental degradation. By doing this research, this paper addresses an important gap in the literature, as few studies have empirically validated a globalization-based EKC across countries and regions using such a comprehensive dataset.

Moreover, this study provides a multidimensional view of globalization by using the KOF Globalization Index, which goes beyond the simple measurement that only uses trade openness as the indicator of globalization level and includes economic, social, and political dimensions. This offers a more sophisticated theoretical approach in the sense that it identifies that globalization is not a one-dimensional process but a complex set of interactions that can have both positive and negative externalities on the environment. By analyzing the regional heterogeneity and moderating effects that human capital brings, the study also provides empirical support for the idea that globalization's environmental impact is conditional on national characteristics. Overall, this research helps to bridge the gap between macroeconomic theory, development studies, and environmental economics.

1.2.2. Practical Significance and Policy Relevance

From a practical perspective, the findings of this study have important policy implications. As countries continue to engage in international trade, capital flows, and cross-border cooperation, understanding how globalization affects environmental sustainability becomes vital for climate action and sustainable development goals.

Firstly, by identifying whether and when globalization begins to reduce environmental degradation, the study offers insight into where countries lie on the globalization–environment curve, helping policymakers determine whether they should prioritize environmental regulation or green investment. For instance, if a country is on the upward slope of the curve, the intervention led by targeted policies might be needed to prevent further environmental harm during early globalization stages. If a country lies on the turning point or the down slope

ISSN: 2710-0170

of the curve, investing in green technologies might be more efficient since the country already has a decent level of globalization, the technology transformation could be the priory factor that could drive the curve downwards. Secondly, the regional heterogeneity analysis provides insights by showing how globalization's environmental consequences differ across Asia, Africa, and Europe which makes policy recommendations that is specific on regions possible. This paper also suggests that low-income countries may need international support to avoid becoming pollution havens, while advanced economies should focus on exporting green technology and governance standards instead of transiting heavy-polluting industries into developing countries with irresponsibility.

2. Literature Review

2.1. Kuznets Curve: Environmental Degradation and Economy Development

The relationship between economic development and environmental degradation has been debated for a long time in environmental economics field. The two dominant hypotheses are the Environmental Kuznets Curve and the Pollution Haven Hypothesis (PHH). Both hypotheses attempt to explain how globalization, trade, and income growth influence environmental quality, though from different theoretical angles. The main idea of Pollution Haven Hypothesis, which is also known as race-to-bottom hypothesis, is that liberalized trade flows allow high-income countries with strict environmental regulations to commit environmentally unsound practices by shifting polluting industries to less developed countries where regulations are relatively lax[3] (Copeland & Taylor, 1995).

The other hypothesis, the Environmental Kuznets Curve, describes that there is an inverted-U shape relationship between economic growth and environmental degradation[4] (Stern et al., 1996). The EKC hypothesis is inspired by Simon Kuznets' (1963) original work on income inequality[5]. Its application to environmental issues was popularized by Grossman and Krueger (1995) during the studies on the NAFTA trade arrangement[6]. They observed that some pollutants, such as sulfur dioxide (SO_2), followed the inverted-U-shaped pattern across countries at different stages of development.

Once EKC has been brought up, a number of studies focusing on estimating whether EKC is true or not appeared. Selden and Song[7] (1994) used cross-country panel data sets to estimate the relationship between emissions per capita and income per capita, and found that there is substantial support for the inverted-U shape hypothesis. By analyzing 10 environmental indicators across 149 countries, Shafik and Bandyopadhyay (1992) used cross-sectional OLS regression method to find out that some indicators (e.g., water pollution) exhibited EKC behavior[8], while others (e.g., CO_2 emissions) did not. While Stern (2004), on the other hand, used time-series data to find that statistical analysis on which the Environmental Kuznets Curve is based on is not robust, therefore, there is hardly any evidence to substantiate the inverted-U shape curve that countries could follow as their capital income rises[9]. He specifically points out that there may be an inverted-U shape relation between urban ambient concentrations of some pollutants and income, which needs to be further tested, but when it comes to the emissions and concentrations, the EKC seems unlikely to be an acceptable model. Overall, with a considerable number of research and advanced econometric techniques like panel cointegration, GMM, and nonlinear ARDL models that have been applied to test the EKC, the results are still mixed, which remains the EKC a contested hypothesis. Critics argue that in many cases, the EKC is more descriptive than explanatory, lacking a clear mechanism for why degradation should decrease after a certain income level[10] (Moomaw & Unruh, 1997).

ISSN: 2710-0170

2.2. The relationship between Environmental Degradation and Globalization

Apart from the literatures focusing on the relationship between environmental degradation and economic development, scholars also have studied the direct relationship between environmental degradation and globalization. As globalization accelerates the integration of economies, societies, and technologies across borders, its environmental consequences have proven to be complex, multi-faceted, and context-dependent.

Early theoretical studies generated both optimistic and pessimistic views. On the one hand, the Pollution Haven Hypothesis suggests that globalization encourages the pollutive industries to relocate into countries with weaker environmental regulations particularly through trade and foreign direct investment, thereby exacerbating environmental degradation in developing economies[11] (Copeland & Taylor, 2004). On the other hand, supporters of the technique effect argue that globalization promotes the spread of cleaner technologies, which can improve environmental quality in the long run[2] (Antweiler et al., 2001).

Empirical evidence on the globalization–environment relationship is mixed. Some studies report that trade with foreign countries contributes to increased pollution and resource depletion, especially in low-income countries[12][13] (Frankel & Rose, 2005; Shafik, 1994). Others find that trade openness, by promoting technological innovation and higher environmental awareness, can reduce environmental degradation after a certain development threshold is reached[14] (Managi et al., 2009). This line of research often based on the Environmental Kuznets Curve framework, proposing an inverted U-shaped relationship between globalization and environmental degradation: as globalization initially rises, environmental quality worsens, but after reaching a turning point, further globalization leads to environmental improvements.

Recent panel data studies provide more subtle and controversial insights. For instance, Shahbaz et al. (2018) find evidence of an inverted U-shaped relationship between trade openness and CO_2 emissions in emerging economies[15], while, Wang et al. (2021) argue that financial and social globalization have differential impacts on various environmental indicators, emphasizing the importance of examining various of the globalization indices separately[16].

Moreover, several studies explore the mechanisms through which globalization affects environmental outcomes. These include technological progress, institutional quality, urbanization, and industrial restructuring. The mediating role of technology is particularly emphasized, with studies showing that globalization-induced R&D spillovers can lead to cleaner production processes and energy efficiency gains[17] (Zhou et al., 2020).

In summary, while there is no general agreement on whether globalization ultimately harms or benefits the environment, most recent studies agree that the relationship is nonlinear and its shape is influenced by environmental indicators, country-specific characteristics and the composition of globalization index itself. Therefore, further research is required to solve these uncertainties and provide more targeted policy recommendations.

3. Methodology

3.1. Research Design

This study uses a quantitative panel data research design to examine the relationship between globalization and environmental degradation across 130 countries from 1996 to 2021. Based on the Environmental Kuznets Curve framework, the model introduces both linear and quadratic terms of globalization to test for a potential inverted U-shaped relationship. Environmental degradation is measured using a composite index constructed via the Entropy Weight Method, incorporating indicators such as gas emissions, energy use, and heavy medal

ISSN: 2710-0170

pollution. Globalization is indicated by the KOF Globalization Index, which includes economic, social, and political dimensions.

To get better understanding of the relationship between the other variables being tested, control variables such as GDP per capita, urbanization, industrial structure, and institutional quality are included. Additionally, interaction terms are used to explore the moderating effect of human capital. The analysis also includes the test of heterogeneity across four continents along with robustness checks of three perspectives: substituting the measurement of independent variable, changing the measurement of dependent variable and changing the observation period.

3.2. Data Source and Sample Selection

We downloaded data from the official websites of EPI, World Bank, and KOF for 233 countries and regions worldwide. However, due to the incomplete data collection for many countries, some countries had to be excluded from the sample, leaving 130 countries from 1996 to 2021. No human intervention was involved in the sample selection process to ensure the samples are selected as randomly as possible. As long as a country has the required data, it is included in the sample.

3.2.1. Dependent variable: Environmental Degradation evaluated with Entropy Weight Method.

Environmental degradation refers to the degradation of the natural environment through the depletion of resources such as air, water, soil, the destruction of ecosystems and the extinction of wildlife. As a global concern, it has been extensively studied from many perspectives including ecology, economics and society. To study its impacts, scholars have developed a wide array of quantitative approaches to assess the degree of environmental degradation across countries.

One of the most widely used proxies is carbon dioxide (CO_2) emissions per capita or total CO_2 emissions. Stern (2004) emphasized CO_2 emissions as a reliable indicator for global environmental pressure, particularly in studies of the Environmental Kuznets Curve[9]. Pao and Tsai (2010) used CO_2 emissions in panel data models to examine the relationship between economic growth and environmental degradation in BRIC countries[18]. While being simple and widely available, CO_2 alone may not capture the full scope of environmental degradation, especially regarding water, land, and biodiversity.

Other indicators are widely used too. For instance, sulfur dioxide (SO_2) emissions were used in early EKC studies like Grossman and Krueger[6] (1995). Biochemical oxygen demand (BOD) in water bodies was used by Shafik and Bandyopadhyay[8] (1992) as a measure of water pollution. Chung (2014) used SO_x, NO_x, CO, PM10, and water waste as pollution indicators[19], while Kearsley and Riddel (2010) employed multiple types of chemical emissions (CO_2, Green House Gas, CO, NO_x, SO_x) along with suspended particulate matter (SPM) and volatile organic compounds (VOCs) to study if pollution haven plays a significant role in influencing the shape of EKC[20]. Afterall, the quantification of environmental degradation is essential for evidence-based policy and international comparison. While early studies relied heavily on single pollution indicators, recent literature favors composite indices and multi-method approaches.

In our research, due to data availability, indicator selection and cross-country comparability, this study is going to use entropy weight method to build our own environmental degradation assessment system and try to be as comprehensive as possible. Entropy weight method assigns higher weights to indicators with greater variability across observations, under the logic that more informative (less uniform) indicators carry more useful information.

The steps of entropy weight method are listed as follows:

Data Normalization

For n periods and m indices, x_{ij} is the value of the sample of j-th index under the i-th period ($i = 1,2\ldots, n; j = 1,2,\ldots, m$). Since the measurement units of various indices are not uniform, they must be standardized before calculating the comprehensive weight, that is, the absolute value of the indicator is converted into a relative value.

For a positive index (the higher, the better):

$$x_{ij} = \frac{x_{ij} - \min\{x_{1j}, \ldots, x_{nj}\}}{\max\{x_{1j}, \ldots, x_{nj}\} - \min\{x_{1j}, \ldots, x_{nj}\}}$$

For a negative index (the lower, the better):

$$x_{ij} = \frac{ma\,x\{x_{1j}, \ldots, x_{nj}\} - x_{ij}}{\max\{x_{1j}, \ldots, x_{nj}\} - \min\{x_{1j}, \ldots, x_{nj}\}}$$

Calculate the proportion of each index

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \, (j = 1,2,3, \ldots, m)$$

p_{ij} stands for the characteristic proportion of the i-th period under the j-th index.

Compute the entropy of each index

$$e_j = -k \sum_{i=1}^{n} p_{ij} \, lnp_{ij}$$

Where $k = 1/\ln(n)$, e_j is the entropy of the j-th index and should be positive permanently.

Calculate the degree of divergence

The degree of divergence of index j is:

$$g_j = 1 - e_j$$

Compute the weight of each indicator

For each indicator, we have to make sure its importance, that is, to give each indicator a weight. The weight for index j is:

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j}$$

Calculate the comprehensive score of each period.

The score of i-th period is:

$$S_i = \sum_{j=1}^{m} w_j x_{ij}$$

Referring to the research of Le and Le[21] (2023) and Cole and Bates[22] (1997) and the consideration of data availability, this article chooses lead exposure, sulfur dioxide emission, nitrogen oxides (NO and NO_2) emissions, fossil fuel consumption (% of total energy consumption) and anthropogenic PM2.5 exposure as the indicators of ED. The assessment system is listed in Table 1.

Table 1: Environmental Degradation Assessment System

Factors	Source	Attributes
Lead Exposure	EPI	Positive
Sulfur Dioxide Emission	EPI	Positive
Nitrogen Oxides (NO and NO2) Emissions	EPI	Positive
Anthropogenic PM2.5 Exposure	EPI	Positive
Fossil Fuel Energy Consumption	EPI	Positive

ISSN: 2710-0170

3.3. Independent Variable: KOF Globalization Index.

The EKC is about level of income and environmental degradation, but our research is about globalization and environmental degradation. Therefore, we have to find a proper and scientific method to examine the level of globalization of the countries.

Globalization, broadly defined as the increasing interactions and connections of countries through trade, investment, information, and culture, has been a central topic in international economics, political science, and sociology. To examine it, former researchers have developed various quantitative methods to measure globalization at the national level. A major trend of evaluating globalization is using Foreign Direct Investment (FDI). However, this paper is not going to use FDI as the indicator of globalization, since it only reflects a small portion of economic globalization and not comprehensive enough.

Since globalization is inherently multidimensional and commonly divided into economic globalization (e.g., trade, capital flows, FDI), social globalization (e.g., international tourism, migration, internet access) and political globalization (e.g., participation in international treaties and organizations), this paper is going to use a well-developed index, the KOF Globalization Index, to quantify the globalization level of each country. The KOF Globalization Index, developed by the KOF Swiss Economic Institute and originally adapted from the work of Dreher[23] (2006) and updated by Dreher et al[24]. (2008), is one of the most comprehensive and widely used indicators of globalization in academic research[25] (Potrafke, 2015). It captures globalization across three main dimensions: economic globalization (including trade, investment flows, and tariffs), social globalization (covering information flows, personal contact, and cultural proximity), and political globalization (such as diplomatic ties, international treaties, and memberships in international organizations). This multidimensional structure offers a more comprehensive view of globalization than indices that only focused on economic aspects.

3.4. Control Variables

GDP per Capita

As an indicator of the economic development level, GDP per Capita is closely related to environmental outcomes. According to the EKC hypothesis, environmental degradation initially increases with the economic development level and then decreases after a certain threshold. Stern (2004) argues that income level must be controlled to avoid attributing the effect of development to globalization alone[9]. Dinda (2004) and Panayotou (1997) emphasize that economic growth affects environmental quality through scale, composition, and technique effects[26].

3.4.1. Industrial Structure

The composition of a country's economy, also known as the share of industry, services, or agriculture in GDP, significantly influences its environmental footprint. Industrial sectors, especially manufacturing and mining, are typically more pollutive than services. Industry often takes a larger part of the country's economy when a country is at its early stages of development, resulting in higher emissions. Cole (2004) finds that pollution levels correlate strongly with industrial sector dominance[1]. Therefore, when studying the relationship between ED and globalization, the composition of a country's economy is an important variable that has to be controlled.

3.4.2. Urbanization

Urbanization affects both the scale and intensity of resource use and pollution. High urban population shares often lead to increased energy consumption, vehicle use, and waste production. York, Rosa, and Dietz (2003) argue that urbanization has independent environmental impacts, apart from income or industrialization[27]. However, Zhang and Lin

ISSN: 2710-0170

(2012) also find that in more developed regions, urbanization can lead to efficiency gains, the enhancing of the awareness of energy-saving and better infrastructure, partially offsetting environmental harm using data from China[28].

3.4.3. Institutional Quality Index

Strong institutions are critical for enforcing environmental regulations, managing natural resources, and ensuring sustainable development. Dasgupta et al. (2006) show that governance quality, such as rule of law, regulatory effectiveness, and corruption control, is significantly associated with environmental performance[29]. Neumayer (2002) found that countries with stronger democratic institutions and more engaged civil society tend to implement and enforce environmental policies better[30].

3.5. Treatment for Missing Observations

For certain variables such as institutional quality index, data were not recorded continuously during the period from 1996 to 2002. In these cases, observations were available for alternate years (which are 1996,1998, and 2000), while intermediate years (which are 1997,1999 and 2001) were missing. To ensure the consistency and continuity in the panel dataset, linear interpolation was employed to address a small number of missing observations. We set the required missing observation point as (x, y), and the missing value is calculated by the following formula:

$$y = (x - x_0)\frac{y_1 - y_0}{x_1 - x_0} + y_0$$

where the value y at x is found by finding the closest existing points (x_0, y_0) and (x_1, y_1), such that $x_0 < x < x_1$ where y_0 and y_1 are observed.

3.6. Summary Statistics

Due to the availability of data, after getting rid of the countries that lack important data we need in the regression, the panel dataset contains 130 countries from every continent, including developed and developing countries with a wide range of income level and development level to ensure the generalizability of the results. For the time period, this paper chooses 1996 to 2021 to eliminate the negative effect that short research time period can bring. A small amount of missing data was filled using linear interpolation method. The variable description is listed in Table 2 and the summary statistics are listed in Table 3.

KOF refers to the KOF Globalization Index (KOF Swiss Economic Institute); EPI refers to the Environmental Performance Index (Yale Center for Environmental Law and Policy, and Center for International Earth Science Information Network, Earth Institute, Columbia University); HDI refers to Human Development Index (Human Development Reports).

All regressions are estimated using StataSE.

Table 2: Variable Description

Variables	Acronyms	Definition
Environmental Degradation	ED	Environmental degradation scores collected from EPI
Globalization Level	GL	Globalization index from KOF
Economic Globalization Level	GLEC	Economic Globalization index from KOF
GDP Per Capita	GDPPC	GDP Per Capita
Urbanization	UB	Ratio of urban population to total population
Industrial Structure	IS	Share of industry of ISIC divisions 10-45 in GDP
Institutional Quality Index	IQI	Worldwide governance indicators from world bank
Methane Emission	CH4	Methane emission (metric tons per year)

ISSN: 2710-0170

Human Capital	HC	Life expectancy index, education index and GNI index

Table 3: Summary Statistics

Variables	Source	Obs.	Mean	Std. Dev.	Min	Max
ED	EPI	3380	0.049	0.07	0	0.918
GL	KOF	3380	60.863	14.829	22.46	89.812
GLEC	KOF	3354	57.887	16.326	19.163	94.102
GDPPC	World Bank	3380	13966.333	18786.446	222.013	112000
UB	World Bank	3380	59.872	22	11.35	100
IS	World Bank	3380	29.093	12.373	2.759	86.67
IQI	World Bank	3380	49.507	28.937	0	100
CH4	EPI	3380	1977.017	5397.453	5.55	61000
HC	HDI	3250	0.713	0.159	0.24	0.969

4. Theoretical Analysis and Research Hypothesis

4.1. Nonlinear Relationship Between Globalization and Environmental Degradation

According to the extended EKC theory, globalization may have an inverted U-shaped relationship with environmental degradation. This nonlinear hypothesis has been explored in previous studies[15][31] (e.g., Shahbaz et al., 2018; Lau et al., 2014), yet empirical consensus remains debatable. Therefore, in this paper, we set the null hypothesis as follows:

H_1: There is an inverted U-shaped relationship between globalization and environmental degradation.

4.2. Regional Heterogeneity of the Globalization–Environment Relationship

The environmental consequences of globalization are unlikely to be consistent across countries or regions. Advanced economies, particularly in Europe, usually have stronger institutional quality, better enforcement of environmental regulations, and higher levels of green technology usage. In contrast, many developing economies in Asia and Africa may experience intensified environmental degradation as they integrate into global markets, particularly through pollutive exports and foreign direct investment. Previous research has emphasized such regional differences[1][12] (Frankel & Rose, 2005; Cole, 2004). To test if this difference exists, this paper makes the null hypothesis as:

H_2: The relationship *between globalization and environmental degradation varies across regions.*

4.3. Human Capital Re-shapes the Relationship Between ED and Globalization

Previous research has highlighted the conditional nature of the impact that globalization is bringing to environmental conditions. While globalization can introduce pollution through industrial expansion, its adverse effects may be mitigated in countries with higher levels of human capital. Educated populations are more capable of adopting green technologies, demanding stronger regulations, and shifting toward less polluting sectors. As such, human capital is expected to shape the direction and intensity of the globalization–environment relationship. To capture this conditionality, this study introduces an interaction term to test the moderating effect. This paper makes the third hypothesis as:

H_3: Human capital positively moderates the effect of globalization on environmental quality.

ISSN: 2710-0170

5. Diagnostic Tests

Before modeling the basic model and doing the regression, we have to run various tests related to the regression to make sure the it is appropriate. In this paper, we are going to run four tests, that are, Wald test, Variance inflation factor, Hausman test, and Likelihood Ratio test. The tests form a coherent validation process: we firstly confirm the usefulness of the model, then ensure the reliability of the variables we chose, and finally select the perfect model.

The results are listed separately in Table 4, Table 5, Table 6 and Table 7.

The Wald test result is statistically significant, indicating that we can reject the null hypothesis that the coefficients on both liner and quadric term are jointly equal to zero. This implies that globalization has a statistically significant non-linear effect on environmental degradation; The Mean VIF equals to 2.43, which generally indicates low multicollinearity. Hausman test results is statistically significant, which suggests us to reject the null hypothesis that individual effects are not correlated with regressors. Therefore, our preferred model is to use fixed effects (FE). From the result of LR test, we can tell that the null hypothesis is significantly rejected, suggesting that these individual-invariant factors are indeed important to consider, which further suggests us to fix both individual and time when building our regression model. In a nutshell, we can assure that a two-way fixed model using panel data is the optimal model to meet our research purpose.

Table 4: Wald Test Results

Wald Test	$F(2, 3244)$	$Prob > F$
	40.43	0.0000

Table 5: Variance Inflation Factor

Variable	VIF	$1/VIF$
GL	3.14	0.318843
IQI	2.99	0.334629
GDPPC	2.53	0.395172
UB	2.28	0.43845
IS	1.22	0.817927
Mean VIF	2.43	

Table 6: Hausman Test Result

	Coefficients			
	FE	RE	Difference	S.E.
GL	0.0023833	0.0024096	-0.0000263	2.02E-05
GL^2	-0.0000188	-0.0000189	8.45E-08	1.54E-07
$GDPPC$	-2.12E-07	-2.22E-07	9.66E-09	2.00E-08
UB	0.0004263	0.0003893	0.0000371	2.29E-05
IS	0.0000883	0.0000926	-4.26E-06	6.63E-06
IQI	-0.0000223	-0.0000273	5.04E-06	5.55E-06
$chi2(6)$	15.2			
$Prob > chi2$	0.0188			

ISSN: 2710-0170

Table 7: LR Test Results

LR Test	LR chi2(25)	Prob > chi2
	44.58	0.0093

6. Empirical Analysis

6.1. The Empirical Model

To empirically examine the potential non-linear relationship between globalization and environmental degradation, we estimate the following baseline model:

$$ED_{it} = \beta_0 + \beta_1 GL_{it} + \beta_2 GL_{it}^2 + \beta_3 Control_{it} + \gamma_t + \mu_i + \varepsilon_{it}$$

Where:

ED_{it} represents the environmental degradation indicator for country i in year t;

GL_{it} measures the degree of globalization;

GL_{it}^2 is the squared term of globalization, included to capture potential non-linear effects;

$Control_{it}$ is a vector of control variables accounting for other economic, institutional, and structural factors; In this paper, the control variables are GDP per capita, industrial structure, urbanization and institutional quality;

γ_t and μ_i represents the individual fixed effect (country fixed effect) and the time fixed effect (year fixed effect) separately;

ε_{it} is the error term;

β_0 is the constant term in the regression model.

The inclusion of both μ_i and γ_t allows the model to control for heterogeneity across countries and time. This fixed effect specification ensures that the estimated relationship between globalization and environmental degradation is not confounded by omitted variables that are either country-specific and irrelevant with time or common across countries but changes with time. By excluding time-invariant and shared temporal influences, we focus on how within-entity changes in variables affect our conclusions.

The key coefficients of interest are β_1 and β_2. A significantly positive sign on β_1 combined with a negative sign on β_2 would indicate an inverted U-shaped relationship, consistent with the Environmental Kuznets Curve hypothesis. This suggests that in the early stages of globalization, environmental degradation worsens, but after a certain threshold, further globalization improves environmental performances.

6.2. Empirical Results

According to the tests results, we can continue to do the baseline regression. The regression results are listed in the following table.

Table 8: Baseline Model Regression Results

	Pooled OLS	RE	Time FE	Two-way FE
GL	0.00549***	0.00241***	0.00238***	0.00246***
	(7.68)	(8.69)	(8.57)	(8.53)
GL^2	-0.0000354***	-0.0000189***	-0.0000188***	-0.0000181***
	(-5.87)	(-7.83)	(-7.78)	(-7.46)
GDPPC	-0.000000240*	-0.000000222*	-0.000000212*	-0.000000104
	(-2.13)	(-2.46)	(-2.30)	(-1.03)
UB	-0.000583***	0.000389***	0.000426***	0.000672***
	(-7.10)	-4.59	(4.85)	-6.45

ISSN: 2710-0170

IS	0.00112***	0.0000926	0.0000883	0.0000213
	(10.4)	(1.63)	(1.54)	(0.36)
IQI	-0.0000255	-0.0000273	-0.0000223	-0.0000389
	(-0.37)	(-0.82)	(-0.66)	(-1.14)
CONS	-0.139***	-0.0454***	-0.0466***	-0.0642***
	(-7.21)	(-4.60)	(-5.82)	(-6.27)
R2	0.1168	0.1084	0.1183	0.1208
N	3380	3380	3380	3380
Year Fixed	NO	NO	NO	YES
Country Fixed	NO	NO	YES	YES

This table also reports regression results using OLS and random effect model. The t statistics are reported in parentheses. ****, ** and * show the coefficients are significant at the 0.1%, 1% and 5% level of significance.*

The statistically significant result of the estimation of β_1 and β_2 supports the existence of an inverted U-shaped curve which is consistent with the EKC hypothesis in the context of globalization. In other words, while globalization initially exacerbates environmental harm, its marginal impact becomes less damaging. But once a certain threshold of globalization is reached, it eventually becomes beneficial.

Regarding to control variables, urban population is positively and significantly associated with environmental degradation, possibly due to the fact that energy consumption, waste generation and traffic emissions are concentrated in densely populated urban areas. In contrast, GDP per capita and industrial structure do not exhibit statistically significant effects in this model, suggesting that, after taking globalization and other factors into consideration, income levels and the share of industry do not independently drive changes in environmental quality within this sample. Similarly, institutional quality is not statistically significant, though it enters with the expected negative sign, hinting at a possible (though weak) role for governance in moderating environmental outcomes.

6.3. Further Discussion: The Turning Point

While the empirical results suggest an inverted-U shaped relationship between globalization and environmental degradation with a turning point indicating where globalization begins to have a positive environmental impact, it is important to point out that surpassing this threshold alone is not sufficient to guarantee environmental improvement.

From an economic perspective, even if a country achieves a high level of globalization, without effective environmental regulation, enforcement, and investment in environmental protection, the benefits of globalization may not materialize. There are many factors that could hold the improvement process back. For example, global trade may continue to drive high carbon exports or encourage resource exploitation if domestic environmental standards remain weak; foreign direct investment with high level of pollution may still flow into countries with loose environmental policy.

From the technological innovation perspective, on the other hand, there are as well some obstacles preventing the environment from getting improved. For example, globalization creates the potential for green technology transfer, but the ability to absorb and implement these technologies is highly uneven across countries. Besides, the fund government spend on R&D in clean energy and resource efficiency is uncertain, which may cause countries fail to convert globalization into environmental gains. The “technology effect” is thus conditional on domestic innovation systems and policy readiness[32] (Popp, 2006).

ISSN: 2710-0170

Overall, the effectiveness of globalization in reducing environmental degradation depends critically on domestic policy responses, particularly in the areas of environmental governance and technological innovation. Crossing the globalization turning point is not a sufficient condition for environmental improvement. Without strong environmental governance, investment in green technology, and strategic structural reforms, globalization alone cannot guarantee a reduction in environmental degradation. Policymakers must combine external integration with internal improvement together to ensure that globalization becomes a force for sustainable development.

7. Robustness Checks

To ensure that the empirical results are not sensitive to choices in variable selection or sample design, we conduct three widely accepted robustness check techniques: replacing the dependent variable, replacing the key independent variable, and modifying the observation period.

7.1. Alternative Measurement of Environmental Degradation

This technique is based on the understanding that complex phenomena such as environmental degradation are multidimensional and cannot be fully captured by a single indicator. By substituting the dependent variable with an alternative indicator, we can test the validity of the model. If the core relationship, that is, the relationship between ED and globalization, remains statistically and economically significant across different environmental indicators, it increases the robustness and generalizability of the findings. This method helps to reduce measurement bias and avoids over-reliance on any single indicator. This approach of robustness check is needed especially under the circumstance that many previous scholars have already drawn conclusion that the shape of the curve is highly related with the choice of the indicators of ED, as we have mentioned in the literature review.

In the first robustness check, we replace the original dependent variable, ED, with an alternative environmental indicator to assess if the results of the baseline regression are driven by the specific environmental indicator we use. In this case, we employ the total amount of CH_4 emissions as the new dependent variable. The alternative specification with CH_4 is presented below:

$$CH_{4it} = \beta_0 + \beta_1 GL_{it} + \beta_2 GL_{it}^2 + \beta_3 Control_{it} + \gamma_t + \mu_i + \varepsilon_{it}$$

The regression result is listed in table 9, column (1).

7.2. Alternative Globalization Index

Globalization, like environmental degradation, is not a directly observable variable. It must be approximated by using composite indicators. Different indices may weigh components differently or focus on different aspects (economic, political, or social globalization). Substituting the key independent variable ensures that the results are not an artifact of index construction, weight assignment, or data aggregation method. This practice addresses indicator sensitivity and supports the external validity of the findings.

To meet the requirements, we substitute the original globalization index (KOF Globalization Index, GL) with an alternative proxy, KOF Economic Globalization Index ($GLEC$), to test if the conclusion still holds, since the paper is more relevant to the study field of economics and $GLEC$ can reflect the trade and economic openness of one country better.

Specification (2):

$$ED_{it} = \beta_0 + \beta_1 GLEC_{it} + \beta_2 GLEC_{it}^2 + \beta_3 Control_{it} + \gamma_t + \mu_i + \varepsilon_{it}$$

ISSN: 2710-0170

The regression result is listed in table 9, column (2). In this regression, the data of KOF Economic Globalization Index for Cuba is missing, leading to a smaller sample size that contains 3354 observation values.

7.3. Subsample: Post-Economic-Crisis Period (2009–Latest Year)

Economic and environmental dynamics often change over time due to technological advances, shifts in regulations, or structural economic transformations. Modifying the time (for instance, by shortening the sample or focusing on recent decades) allows us to test the temporal stability of the estimated relationship. This approach addresses concerns about structural breaks, historical dependency, or data quality issues in earlier years[33] (Dinda, 2004). Consistent results across different years enhance the temporal robustness and credibility of the conclusions.

To test whether the relationship between globalization and environmental degradation is driven by global macroeconomic shocks, we re-estimate the model using a subsample restricted to the post-2008 financial crisis period. This approach controls for structural breaks and global policy shifts that may have altered the nature of globalization's impact on the environment. The model remains unchanged from the baseline model.

The regression result is listed in table 9, column (3).

Table 9: Robustness Check Results

	(1)	(2)	(3)
GL	63.10***		0.00259**
	(3.94)		(3.13)
GL2	-0.456***		-0.0000229***
	(-3.38)		(-3.41)
GDPPC	0.0179**	-0.000000322***	-0.000000776***
	(3.21)	(-3.37)	(-4.99)
UB	82.42***	0.000608***	-0.00211***
	(14.21)	(5.75)	(-8.14)
IS	-0.103	0.000105	0.000270**
	(-0.03)	(1.83)	(3.22)
IQI	4.103*	0.00000874	-0.000110*
	(2.15)	(0.26)	(-1.98)
GLEC		0.00159***	
		(7.25)	
GLEC2		-0.0000150***	
		(-7.71)	
CONS	-5196.8***	-0.0268**	0.118***
	(-9.12)	(-3.14)	(3.89)
R2	0.1135	0.0665	0.1040
N	3380	3354	1690

In specification (1), the inverted U-shaped relationship between globalization and environmental degradation remains statistically significant, with the sign and magnitude of the coefficients on globalization and its squared term broadly consistent with the baseline results. This suggests that the identified non-linear pattern is not sensitive to the specific environmental measure chosen.

From the results of specification (2), we can come to the conclusion that the key non-linear relationship persists: the linear term remains positive while the squared term remains negative

ISSN: 2710-0170

and significant. This further confirms that the U-shaped effect is robust across different conceptualizations of globalization.

In column (3), the results remain qualitatively unchanged, with the inverted U-shaped pattern still present, suggesting that the main findings still significantly hold after the global economic crisis.

From the results above, we can tell that these robustness check results provide scientifically sound proves for verifying the consistency and reliability of the empirical model. They address the issues that indicator choice and sample variation can possibly bring which are recognized as the main sources of potential bias in econometric modeling and estimating.

It is worth noting that the magnitude of the coefficients in column (1) differs substantially from the baseline regression. This is primarily due to the difference in the scale and units of the dependent variable. While the original environmental degradation index was a normalized comprehensive score ranging from 0 to 1, the alternative measure, total CH_4 emissions, is expressed in absolute units (kilotons).

8. Heterogeneity Analysis

To further explore the contextual variation in the relationship between globalization and environmental degradation, this study conducts a heterogeneity analysis by dividing the full sample into three major regional groups: Asia, Africa, Europe and America (some countries are discarded since they do not belong to any of those continents above and if being included and regressed as a single group, the sample size would be too small). Separate regressions are performed for each subgroup.

Because of the existence of the Simpson's paradox which is a phenomenon that a trend appears in several groups of data but disappears or reverses when the groups are combined, doing the heterogeneity analysis becomes a must. The primary purpose of this analysis is to assess whether the estimated effects of globalization on the environment vary across regions with different economic structures, institutional capacities, and stages of globalization. While the baseline model estimates an average effect across all countries, such a pooled regression may mask underlying regional disparities. Furthermore, to speak in a realistic level, heterogeneity analysis also helps us to give policy advises to each country based on its structural and developmental realities.

The main rationale for grouping the sample based on regions is development level. The three regions differ significantly in terms of income levels, industrialization, urbanization, and institutional quality—all of which may influence how globalization interacts with environmental performance.

The separated grouping results are listed as follows. From Table 10 we can tell that after grouping the samples and running regressions, every R^2 of the grouped regression are higher than R^2 of the baseline regression. This suggests that structural heterogeneity exists between groups, which dilutes the explanatory power of the overall regression, which further suggests that grouped regressions can help reveal more realistic mechanisms.

To look in details, in Europe, the estimated coefficients are statistically significant and largely consistent with the baseline model. This suggests that globalization in European countries follows the predicted inverted-U pattern, where early-stage globalization leads to environmental degradation, but advanced globalization levels contribute to environmental improvement. The similar thing happens in Africa and America, where the sign of the coefficients of GL and GL^2 are all consistent with the baseline model and significant at 0.1% significant level. However, in Asian subgroup, although the coefficients seem do not have a big difference with the baseline regression, they are not as statistically significant as the baseline regression. The coefficients are significant at 1% level.

ISSN: 2710-0170

Based on the result and existing literature, we can make a series of inferences to come up with a possible and reasonable explanation for this phenomenon. Asian countries are diverse and at different stages of economic development and globalization, ranging from highly globalized and developed economies like Japan and Singapore to large and emerging economies such as China, India, and Indonesia. This heterogeneity leads to mixed and vague trends. In middle-income countries, globalization may still be driving pollution through industrial expansion and weak environmental enforcement. Meanwhile, high-income Asian countries may already benefit from green globalization effects, such as innovation and regulation. This internal diversity within the region may weaken the statistical significance of the estimated coefficients.

In addition to regional differences in coefficient significance, the regression results also reveal variation in the curvature of the globalization–environment relationship across regions. Specifically, the quadratic term (GL^2) in the Africa subgroup has the smallest absolute value, indicating a flatter curve, while the America, Europe and Asia exhibit relatively steeper curves. But the turning points in terms of globalization are similar across all groups.

The flatter curve in Africa suggests that the marginal effect of globalization on environmental degradation changes more gradually. There are some possible explanations. Firstly, the lower variation in globalization causes the estimator which makes the curve flatter. African countries may be more concentrated in the early or middle stages of globalization. A narrower range of globalization exposure reduces the curvature, leading to more linear patterns. The second reason is the slower institutional and technological response. Due to limited capacity to absorb advanced technology or enforce environmental policies, the potential of globalization to reduce degradation at higher levels is less performed. As a result, the decline that happens after the peak in environmental harm is more modest.

In contrast, regions like Europe and the America with steeper curves are more likely to experience quicker environmental payoffs from globalization, possibly due to stronger institutions, advanced technologies, and diversified economies. Asia, with the steepest curve, reflects both strong globalization momentum and rising internal capacity to switch to sustainable growth.

This phenomenon provides some inspiration for policymakers. In Africa, policymakers may not witness immediate environmental benefits even after surpassing the turning point. More targeted interventions are needed to make globalization actually be beneficial to environment, especially in technology diffusion, education, and green infrastructure. However, in Asia, Europe and the Americas where the curves are steeper, the sharper response implies that once key reforms are in place, globalization can become a stronger force for sustainability, but risks are also greater if the regulations and technological investments are poorly conducted. Therefore, when making environmental policies and decisions, the government in Asia, Europe and America should be more careful.

Table 10: Heterogeneity Analysis

	Asia	Africa	Europe	America
GL	0.00274*	0.000725***	0.00245***	0.00192***
	(2.53)	(6.51)	(12.36)	(5.04)
GL2	-0.0000201*	-0.00000524***	-0.0000168***	-0.0000175***
	(-2.08)	(-4.81)	(-10.15)	(-5.56)
GDPPC	-0.000000223	0.000000152*	0.000000395***	-0.00000105***
	(-0.73)	(1.98)	(8.17)	(-5.68)
UB	0.00145***	0.000319***	0.000405***	0.0000727
	(3.64)	(8.26)	(5.84)	(0.97)

ISSN: 2710-0170

IS	-0.000209	0.0000236	-0.00000389	0.000179**
	(-1.06)	(1.48)	(-0.06)	(3)
IQI	-0.000244	0.0000511***	0.0000232	-0.000107***
	(-1.65)	(4.96)	(1.15)	(-3.59)
CON	-0.0657	-0.0106**	-0.0767***	-0.00632
	(-1.70)	(-3.09)	(-10.49)	(-0.54)
R2	0.1315	0.4214	0.5260	0.2527
N	806	910	1092	520

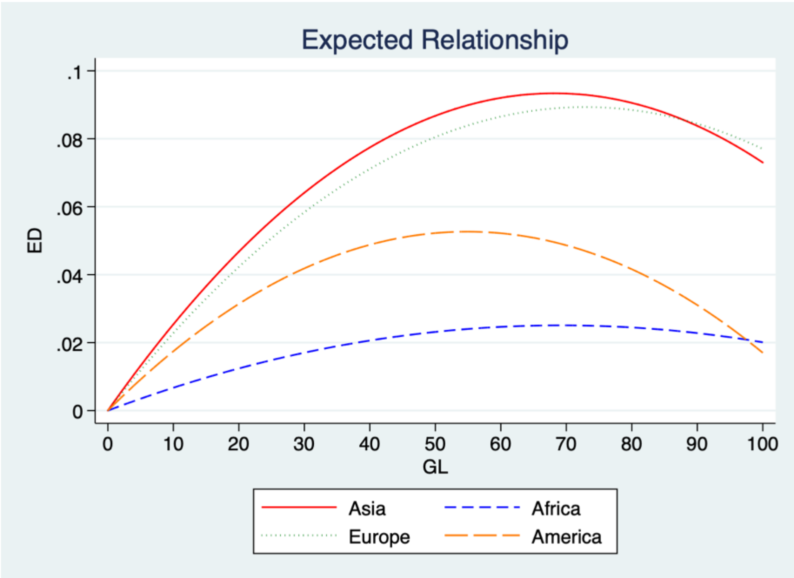

Figure 1: Heterogeneity Analysis

9. Moderation Analysis

9.1. The Importance of Moderation Analysis

A moderating effect occurs when the strength or direction of the relationship between an independent variable and a dependent variable changes depending on the level of a third variable—known as the moderator. In our research, we choose the Human Capital as the moderator and test whether human capital moderates the relationship between globalization and environmental degradation.

The inclusion of a moderating variable helps to uncover conditional relationships that are not directly observable in simple models. Specifically, the impact of globalization on environmental outcomes may not be consistent across countries: it can depend significantly on their level of human capital. Exploring such interactions enhances the explanatory power of the model and provides more detailed policy insights.

9.2. Justifications for Choosing Human Capital as the Moderator

Human capital, in this paper, typically measured through indicators as GNI index, education index, and life expectancy index, reflects a country's education level, skill level, knowledge base and life quality. There are several theoretical and empirical reasons to justify that human capital can influence how globalization affects the environment. Firstly, highly educated workforces are better equipped to adopt and implement environmental-friendly technologies. As globalization introduces new technologies through trade and foreign investment, countries with higher human capital are more likely to absorb and utilize these technologies efficiently,

ISSN: 2710-0170

thereby reducing environmental harm. Barro (2001) emphasizes the role of education in enhancing countries' ability to benefit from international technological diffusion[34]. Later, Borghesi and Vercelli (2003) argue that higher education levels help shift production toward less polluting sectors[35].

Secondly, a country with more educated population tends to be more environmentally conscious and more likely to demand better environmental protection and regulation. This pressure given by citizens can lead to more restricted environmental standards and policies. López and Mitra (2000) suggest that education is positively correlated with environmental preferences, leading to stronger political support for environmental regulation[36]. Neumayer (2002) finds that countries with higher education levels tend to adopt stronger environmental regulations and commitments[29].

The third justification is that human capital can help shift a country's comparative advantage away from resource-intensive or pollution-intensive sectors. As the research of Dasgupta et al. (2002) shows, human capital development is associated with cleaner industrial structures and stronger environmental performance[37]. By supporting the development of knowledge-intensive industries, it reduces dependence on "dirty" exports that often flourish in early stages of globalization.

In summary, human capital is not only a factor of production ability but also influences how countries respond to the challenges and opportunities brought by globalization. By including it as a moderating variable, it captures the differentiated ability of countries to leverage globalization in an environmentally sustainable way. Therefore, we can extend our hypothesis as follows:

H_3: Human capital moderates the relationship *between globalization and environmental quality.*

9.3. Building the Moderating Analysis Model

In this study, the moderating effect of human capital is tested by including an interaction term between globalization and human capital in the regression model. We build the model as follows:

$$ED_{it} = \beta_0 + \beta_1 GL_{it} + \beta_2 GL_{it}^2 + +\beta_3 HC_{it} + \beta_4 GL_{it} \times HC_{it} + \beta_5 GL_{it}^2 \times HC_{it} + \beta_6 Control_{it} + \gamma_t + \mu_i + \varepsilon_{it}$$

9.4. Results Analysis and Discussion

Table 11: Moderating Analysis Results

	(1)
GL	-0.00761***
	(-7.57)
GL^2	0.0000897***
	(7.67)
HC	-0.0755*
	(-2.01)
GL×HC	0.0100***
	(8.21)
GL^2 ×HC	-0.000117***
	(-9.67)
GDPPC	0.000000193
	(1.8)

ISSN: 2710-0170

UB	0.000249*
	(2.26)
IS	-0.0000268
	(-0.45)
IQI	-0.0000847*
	(-2.37)
CONS	0.107***
	(4.3)
R2	0.116
N	3250

Table 11 presents the regression results examining the moderating effect of human capital on the relationship between globalization and environmental degradation. Columns (1) include both the linear and quadratic terms of globalization, human capital, and their respective interaction terms.

We can witness a change in the coefficient of the linear and quadratic terms of globalization. The sign of the coefficient of the GL becomes negative, in contrast to its positive counterpart in the baseline model; similarly, the coefficient of quadratic term of globalization becomes positive. It does not represent an estimation error or occurs in the regression or model. In fact, the coefficient β_1 no longer represents the average marginal effect of globalization on environmental degradation. Instead, it captures the effect of globalization when the moderator, Human Capital, is equal to zero. Since $HC = 0$ lies outside of the range of observed data and has no practical interpretation, the coefficient β_1 alone is not meaningful if isolated. The actual marginal effect of globalization on environmental degradation is conditional on the values of both environmental degradation and human capital, as captured by the following partial derivative:

$$\frac{\partial ED}{\partial GL} = \beta_1 + 2\beta_2 GL + \beta_4 HC + 2\beta_5 GL \times HC$$

The similar situation happens to the coefficient of GL^2. In order to find the true effect of globalization can bring to environmental degradation, we have to use the second derivative as follows:

$$\frac{\partial^2 ED}{\partial GL^2} = 2\beta_2 + 2\beta_5 HC$$

As the algorithm shows, the curvature depends on the value of human capital. In other words, the curvature of the relationship between globalization and environmental degradation is not fixed, but varies across different levels of human capital.

Human capital itself exhibits a negative and statistically significant coefficient, suggesting that higher levels of education and skill are directly associated with improving environmental outcomes. This is consistent with previous studies indicating that educated populations are more environmentally aware and supportive for sustainable policies[30][36] (Neumayer, 2002; López & Mitra, 2000).

Most notably, the interaction terms reveal a significant moderating effect of human capital. The coefficient on the interaction between globalization and human capital ($GL \times HC$) is positive and highly significant, indicating that in countries with higher levels of human capital, globalization contributes more strongly to environmental improvement. This suggests that

ISSN: 2710-0170

human capital enhances a country's capacity to absorb green technologies, enforce regulations, and transition toward cleaner industries.

Furthermore, the squared interaction term ($GL^2 \times HC$) is negative and strongly significant, implying that the turning point of the globalization-environment curve is shifted depending on the level of human capital. In countries with more developed human capital, the inverted U-shaped curve becomes steeper, indicating that when the same amount of globalization level is changed, the ED changes more compared to countries with lower human capital. This suggests that investment in education may accelerate the transition from environmentally harmful to environmentally beneficial stages of globalization.

Overall, these results substantiate the critical role of human capital as a moderating factor. Globalization alone does not guarantee environmental benefits, but in the presence of strong human capital, its negative effects can be mitigated, and its positive spillovers can be more effectively realized.

10. Conclusion, Policy Advice and Limitations

This study explores the non-linear relationship between globalization and environmental degradation by testing three core hypotheses using panel data from 130 countries over the period of 1996 to 2021. This paper provides evidence for a non-linear curve in the globalization–environment nexus, identifies regional heterogeneity, and confirms that human capital plays a moderating role in shaping globalization's environmental impact. Based on these findings, the purpose of this section is to summarizes the conclusions and presents targeted policy implications based on each hypothesis.

The regression analysis confirms the existence of a statistically significant inverted U-shaped relationship between globalization and environmental degradation, which is consistent with the EKC hypothesis. At low to moderate levels of globalization, countries tend to experience increased environmental degradation—likely due to industrial expansion and weak regulations and foreign direct investments. However, after surpassing a certain globalization threshold, the relationship reverses and the curve bends downwards: further globalization leads to environmental improvements, possibly through technology transfer, institutional alignment, and increased environmental awareness. This finding implies that globalization is not inherently harmful to the environment, but its effects depend on the level of integration and accompanying national conditions. For countries currently on the upward-sloping part of the curve, caution is needed in accelerating globalization without harming the environment further. These countries should implement transition policies, such as environmental regulation, taxing on pollution and industrial upgrading to avoid irreversible ecological damage. Meanwhile, countries that have crossed the turning point should further fully utilize globalization to promote green growth, including clean energy trade, environmental technology imports, and international environmental cooperation.

This study also finds evidence of regional heterogeneity in the globalization-environment relationship. First, the effect is statistically significant in Europe, Africa, and the Americas, but only weakly significant in Asia, suggesting that the relationship is less robust in Asian countries, possibly due to bigger internal structural diversity compared to Europe and Africa. Second, the African subgroup illustrates a flatter trend, indicating that the environmental impact of globalization changes more gradually and less intensely over time. This contrasts with the steeper curves in other regions, where globalization produces more rapid shifts in environmental performances. As a result of regional heterogeneity, policy implications should vary accordingly. For instance, in Africa, gradual change calls for long-term investments in education, environmental regulation, and clean technology to strengthen globalization's positive effects. In addition to African countries' own effort, international support is essential

ISSN: 2710-0170

to prevent the region from becoming a "pollution haven" as well. Multilateral donors and development agencies should provide targeted technical and financial assistance to build environmental regulatory capacity and support green infrastructure, ensuring that globalization benefits (such as economic growth) are not achieved at the cost of environmental degradation.

The moderating analysis demonstrates that human capital significantly moderates the globalization–environment relationship. Countries with higher levels of education and skills experience less environmental harm from globalization and reach the EKC turning point earlier. The interaction terms in the model are statistically significant and imply that human capital not only reduces the marginal damage of globalization but also facilitates the transition toward environmentally beneficial phases. This suggests that environmental sustainability under globalization is not automatic, but conditional on internal capabilities, particularly in knowledge and education.

Given these results, policymakers must recognize that investment in human capital is a key driver of environmentally sustainable globalization. Educational reforms aimed at enhancing environmental literacy, science and engineering training, and green innovation skills can significantly improve a country's ability to absorb clean technologies, implement environmental policies, and support ecological transitions. There are some suggestions that may help policymakers. First of all, the government should integrate environmental topics into national education curricula at all levels to raise the citizens' environmental awareness. Secondly, the government should promote technical training for positions in industries affected by trade and foreign investment. Thirdly, the government should support research and development in clean technology, particularly through universities' collaboration with industry.

However, although the regression results suggest an inverted U-shaped relationship between globalization and environmental degradation, the evidence should be interpreted with caution. First, the dataset employed in this study covers only 130 countries, which indeed more extensive and comprehensive than previous similar studies, does not represent the full global situation. Several extremely underdeveloped nations are excluded due to missing or unreliable data, particularly in terms of environmental indicators and globalization indices. This incomplete data may cause selection bias, affecting the generalizability of the results. In other words, the process of data collection is unlikely to be entirely random although the data collection process is procedurally random. We downloaded data from all 233 countries and regions around the world, and then excluded countries that did not have statistical data on environmental degradation, globalization and other control variables. There was no special selection of the sample in the procedure. However, it is these countries with inadequate institutional capacity, poor statistical infrastructure, or political instability that are often absent from international databases such as the KOF Globalization Index or World Bank environmental indicators. This omission results in a non-random sample that may bias the trajectory of the globalization-environment relationship toward more stable or developed economies, where turning points in the curve can be more easily observed.

References

[1]Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. Ecological economics, 48(1), 71-81.

[2]Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment?. American economic review, 91(4), 877-908.

[3]Copeland, B. R., & Taylor, M. S. (1995). Trade and the environment: a partial synthesis. American Journal of Agricultural Economics, 77(3), 765-771.

ISSN: 2710-0170

[4]Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development. World development, 24(7), 1151-1160.
[5]Kuznets, S. (1963). Quantitative aspects of the economic growth of nations: VIII. Distribution of income by size. Economic development and cultural change, 11(2, Part 2), 1-80.
[6]Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. The quarterly journal of economics, 110(2), 353-377.
[7]Selden, T. M., & Song, D. (1994). Environmental quality and development: is there a Kuznets curve for air pollution emissions?. Journal of Environmental Economics and management, 27(2), 147-162.
[8]Shafik, N., & Bandyopadhyay, S. (1992). Economic growth and environmental quality: time-series and cross-country evidence (Vol. 904). World Bank Publications.
[9]Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. World development, 32(8), 1419-1439.
[10]Moomaw, W. R., & Unruh, G. C. (1997). Are environmental Kuznets curves misleading us? The case of CO2 emissions. Environment and development economics, 2(4), 451-463.
[11]Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. Journal of Economic literature, 42(1), 7-71.
[12]Frankel, J. A., & Rose, A. K. (2005). Is trade good or bad for the environment? Sorting out the causality. Review of economics and statistics, 87(1), 85-91.
[13]Shafik, N. (1994). Economic development and environmental quality: an econometric analysis. Oxford economic papers, 46(Supplement_1), 757-773.
[14]Managi, S., Hibiki, A., & Tsurumi, T. (2009). Does trade openness improve environmental quality?. Journal of environmental economics and management, 58(3), 346-363.
[15]Shahbaz, M., Zakaria, M., Shahzad, S. J. H., & Mahalik, M. K. (2018). The energy consumption and economic growth nexus in top ten energy-consuming countries: Fresh evidence from using the quantile-on-quantile approach. Energy Economics, 71, 282-301.
[16]Wang, F., Wang, R., & He, Z. (2021). The impact of environmental pollution and green finance on the high-quality development of energy based on spatial Dubin model. Resources Policy, 74, 102451.
[17]Zhou, X., Yang, S., & Wang, G. (2020). Impacts of knowledge spillovers and cartelization on cooperative innovation decisions with uncertain technology efficiency. Computers & Industrial Engineering, 143, 106395.
[18]Pao, H. T., & Tsai, C. M. (2010). CO2 emissions, energy consumption and economic growth in BRIC countries. Energy policy, 38(12), 7850-7860.
[19] Chung, S. (2014). Environmental regulation and foreign direct investment: Evidence from South Korea. Journal of Development Economics, 108, 222-236.
[20]Kearsley, A., & Riddel, M. (2010). A further inquiry into the pollution haven hypothesis and the environmental Kuznets curve. Ecological Economics, 69(4), 905-919.
[21]Le, H. C., & Le, T. H. (2023). Effects of economic, social, and political globalization on environmental quality: international evidence. Environment, Development and Sustainability, 25(5), 4269-4299.
[22]Cole, M. A., Rayner, A. J., & Bates, J. M. (1997). The environmental Kuznets curve: an empirical analysis. Environment and development economics, 2(4), 401-416.
[23]Dreher, A. (2006). Does globalization affect growth? Evidence from a new index of globalization. Applied economics, 38(10), 1091-1110.
[24]Dreher, A., & Gaston, N. (2008). Has globalization increased inequality?. Review of International Economics, 16(3), 516-536.
[25]Potrafke, N. (2015). The evidence on globalisation. The World Economy, 38(3), 509-552.
[26]Panayotou, T. (1997). Demystifying the environmental Kuznets curve: turning a black box into a policy tool. Environment and development economics, 2(4), 465-484
[27]York, R., Rosa, E. A., & Dietz, T. (2003). Footprints on the earth: The environmental consequences of modernity. American sociological review, 68(2), 279-300.

ISSN: 2710-0170

[28]Zhang, C., & Lin, Y. (2012). Panel estimation for urbanization, energy consumption and CO2 emissions: A regional analysis in China. Energy policy, 49, 488-498.

[29]Dasgupta, S., Hamilton, K., Pandey, K. D., & Wheeler, D. (2006). Environment during growth: accounting for governance and vulnerability. World development, 34(9), 1597-1611.

[30]Neumayer, E. (2002). Do democracies exhibit stronger international environmental commitment? A cross-country analysis. Journal of peace research, 39(2), 139-164.

[31]Lau, L. S., Choong, C. K., & Eng, Y. K. (2014). Investigation of the environmental Kuznets curve for carbon emissions in Malaysia: do foreign direct investment and trade matter?. Energy policy, 68, 490-497.

[32]Popp, D. (2006). International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. Journal of Environmental Economics and Management, 51(1), 46-71.

[33]Dinda, S. (2004). Environmental Kuznets curve hypothesis: a survey. Ecological economics, 49(4), 431-455.

[34]Barro, R. J. (2001). Human capital and growth. American economic review, 91(2), 12-17.

inequality?. European Journal of political economy, 26(4), 488-505.

[35]Borghesi, S., & Vercelli, A. (2003). Sustainable globalisation. Ecological Economics, 44(1), 77-89.

[36]Lopez, R., & Mitra, S. (2000). Corruption, pollution, and the Kuznets environment curve. Journal of environmental economics and management, 40(2), 137-150.

[37]Dasgupta, S., Laplante, B., Wang, H., & Wheeler, D. (2002). Confronting the environmental Kuznets curve. Journal of economic perspectives, 16(1), 147-168.