

# **Examining Linkages between Economic Growth and Environmental Degradation: A Cross-Country Analysis**

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## Abstract

*This paper tries to explore the linkages between Economic growth and Environmental degradation through panel data analysis. Economic growth is measured in terms of GDP per capita and Environmental degradation is captured in terms of Carbon-dioxide emissions per capita. Relationship of some other explanatory variables like ICT, dependency ratio, urbanisation and renewable energy consumption are also observed with respect to environmental degradation. FEMs and REMs are employed in the panel data to estimate the above-mentioned relationship. A panel of around 200 countries has been obtained from WDI database, for a time-period stretching from 1970 to 2023. The paper tries to also explore the relevance of EKC using CO<sub>2</sub> emissions as the pollutant, for the panel consisting all the countries including in WDI, and for countries categorised as per World-Bank's income criterion (HICs, LICs, LMICs & UMICs). For establishing EKC (of inverted U-shape), a quadratic form of GDP per capita has been introduced as an independent variable. Logarithmic forms of GDP per capita and CO<sub>2</sub> emissions per capita have been used. The paper also incorporates the use of GAM to check for the linearity in relationships between the variables of interest. The analyses performed in the paper highlights a mixed result on the relevance of EKC: the LICs, LMICs and the panel consisting all the countries exhibit an inverted U-shaped curve. On the contrary, HICs and UMICs do not show the existence of an inverted U-shaped EKC.*

**Keywords:** *Economic Growth, Environmental degradation, EKC, FEMs, REMs, GAM, inverted U-shaped*

**JEL codes:** *Q56, Q50, Q54, N50, O13, Q20*

# 1. Introduction:

The relationship between economic growth and environmental degradation has emerged as a critical area of inquiry for economists and policymakers worldwide. As nations pursue economic development, concerns about environmental sustainability and the long-term consequences of unchecked growth have intensified. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation initially increases with economic growth but eventually declines after reaching a certain income level (Grossman & Krueger, 1995). This non-linear relationship underpins a substantial body of empirical research attempting to ascertain whether economic progress inevitably exacerbates environmental harm or if it can eventually lead to ecological improvements. In the context of the 21st century's where we witness escalating environmental crises including climate change, biodiversity loss, and resource depletion, understanding this dynamic becomes vital for crafting sustainable economic policies (Stern, 2004).

India, as one of the fastest-growing major economies, faces a complex challenge of balancing robust economic growth with environmental sustainability. The Economic Survey of India (2023) emphasizes the need for a transition to a green economy while maintaining economic momentum. With rising levels of carbon emissions, air pollution, and resource consumption, India's developmental trajectory poses significant questions about the trade-offs between growth and environmental preservation. Moreover, India's commitment to achieving Net Zero by 2070 (announced at COP26) underlines the urgency of examining these linkages to inform policy frameworks that align with both economic and ecological goals (Ministry of Finance, 2023).

The present study conducts a cross-country analysis of the relationship between economic growth and environmental degradation using the Environmental Kuznets Curve framework and additional explanatory variables. This approach allows for a comparative perspective, shedding light on how different nations at various developmental stages manage the growth-environment trade-off. Specifically, this study distinguishes between country groups based on the World Bank's income classification: low-income, lower-middle-income, upper-middle-income, and high-income- to identify whether the EKC pattern holds consistently across different economic contexts. Such a disaggregated approach reveals heterogeneity in environmental responses to economic growth, enabling more tailored policy prescriptions. Cross-country analysis is particularly relevant given the transboundary nature of environmental degradation. Issues such as greenhouse gas emissions, air and water pollution, and biodiversity loss do not respect national borders, necessitating a global perspective. The Intergovernmental Panel on Climate Change (IPCC) underscores the need for

international cooperation to mitigate cross-border environmental impacts (IPCC, 2023). By analysing diverse countries, this study highlights best practices and common pitfalls, offering valuable lessons for emerging economies like India. Understanding how other nations balance growth with environmental sustainability can inform India's policymaking, fostering an evidence-based approach to achieve both developmental and ecological objectives.

Furthermore, the study acknowledges the principle of intergenerational equity, which emphasizes the responsibility to preserve environmental resources for future generations. The Brundtland Commission's report (1987) articulated the concept of sustainable development as meeting "the needs of the present without compromising the ability of future generations to meet their own needs." This principle is particularly pertinent for developing and under-developed nations, where rapid urbanization and industrialization risk compromising environmental health for future citizens. By examining the growth-environment nexus across countries, the research provides insights into how policy frameworks can reconcile immediate economic ambitions with the ethical obligation to protect ecological systems for future generations.

Through rigorous empirical analysis spanning multiple nations and income groups, this study offers a comprehensive assessment of the Environmental Kuznets Curve hypothesis and the broader dynamics between economic growth and environmental degradation. The findings will not only enhance theoretical understanding but also contribute to the formulation of policies that balance economic aspirations with environmental stewardship. Given India's position on the cusp of transformative economic change, such insights are indispensable for navigating the delicate balance between progress and sustainability.

According to the World Development Indicators (WDI), CO<sub>2</sub> emissions exhibit significant variation across income levels. High-income countries, owing to advanced industrialization, historically contribute the largest share of global emissions. In contrast, low-income countries display lower emissions but show rising trends as economic activities increase. By using log<sub>10</sub>, variations among low and medium emitters become more visible. It compresses large values while spreading out small values, enhancing readability. Without logs, many low-emission countries would appear almost identical (all in dark green). The log scale allows more detailed differentiation across the full range.

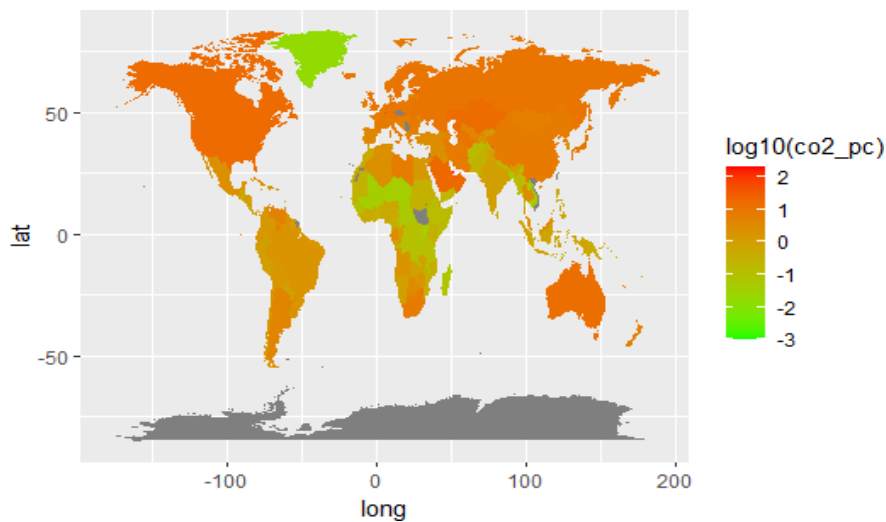


Figure 1: Global CO<sub>2</sub> emissions per capita, source: WDI

#### Delving into Regional Variations in CO<sub>2</sub> Emissions per Capita:

- High CO<sub>2</sub> per capita (Red to Orange,  $\log_{10} \approx 1$  to  $2$ )- Regions of North America (USA, Canada) have very high emissions due to heavy industrialization, high energy consumption, and car dependency. The European region (Western & Northern) is industrialized but with better energy efficiency and renewable, leading to slightly lower emissions. Gulf countries (Middle East- UAE, Qatar, Kuwait): have extremely high emissions due to fossil fuel extraction, small populations, and high energy use.
- Moderate CO<sub>2</sub> per capita (Yellow to Light Green,  $\log_{10} \approx 0$  to  $1$ ) - China & Russia are major industrial powerhouses with high coal consumption but large populations, leading to moderate per capita values. Countries like Brazil, India, and Indonesia in South America & South Asia have moderate emissions due to rapid urbanization but lower per capita energy use compared to Western nations.
- Low CO<sub>2</sub> per capita (Green to Dark Green,  $\log_{10} \approx -1$  to  $-3$ )- Regions of Sub-Saharan Africa have low emissions due to minimal industrialization and low energy access. Some parts of South and Southeast Asia have high rural populations with low energy use. Pacific Island nations very low CO<sub>2</sub> emissions due to small economies and limited fossil fuel use.

Empirical data from 1970 to 2023 reveals a substantial increase in global CO<sub>2</sub> emissions per capita. High-income countries typically exhibit a plateau or decline due to the adoption of cleaner technologies and stringent environmental regulations. However, emerging economies continue to experience rising emissions as they prioritize economic development over environmental considerations. This study's comprehensive cross-country approach, using the World Bank's income classification, allows for a deeper understanding of these patterns and whether the Environmental Kuznets Curve (EKC) hypothesis holds true across various income levels.

**Theoretical Background:** The Environmental Kuznets Curve (EKC) hypothesis, first introduced by [Grossman and Krueger \(1991, 1995\)](#), suggests a unique relationship between economic growth and environmental degradation. It argues that as an economy grows, environmental quality initially worsens but eventually improves after reaching a certain level of income. This relationship forms an inverted U-shaped curve. In the early stages of development, industrialization increases pollution due to a heavy reliance on natural resources and weak environmental regulations. However, as income rises, societies demand cleaner environments, leading to better technology, stronger regulations, and a shift towards less-polluting industries. This results in a reduction in environmental damage despite continued economic growth. Grossman and Krueger's work, originally examining the environmental impacts of trade under the North American Free Trade Agreement (NAFTA), highlighted how economic progress could eventually lead to environmental improvements. Their findings sparked a global debate on whether growth alone can solve environmental challenges or if proactive policies are essential. The EKC remains a central framework in environmental economics, but it is not universal as different pollutants and countries show varying patterns. Nevertheless, it emphasizes the complex link between growth and environmental sustainability, suggesting that with the right policies, economic development can coexist with environmental protection.

The primary objectives of this study are to examine whether the Environmental Kuznets Curve (EKC) hypothesis holds, with a particular focus on its inverted U-shaped relationship between economic growth and environmental degradation. It aims to analyse the shape of the EKC at the global level and investigate EKC dynamics across countries classified by the World Bank into different income groups through category-specific analysis. Additionally, the study seeks to understand the impact of other explanatory variables on environmental degradation, including urbanization, technological advancement, population aging, and energy transition.

## 2. Review of Literature:

A substantial body of empirical research has investigated the Environmental Kuznets Curve (EKC) hypothesis using various pollutants, methodologies, and geographic scopes. [Shafik and Bandyopadhyay \(1992\)](#) and [Torras and Boyce \(1998\)](#) examined pollutant concentrations using locational dummies and socio-economic variables, respectively, across multiple countries from the Global Environmental Monitoring System (GEMS). Both studies found evidence supporting the EKC hypothesis. Similarly, [Grossman and Krueger \(1994\)](#) utilized data from 52 cities across 32 countries but did not find consistent support for the EKC when controlling for locational factors and population density. [Panayotou \(1997\)](#), focusing on policy variables and population density in 30 countries, also found mixed evidence, suggesting the role of institutional factors in shaping environmental outcomes.

Moving to emission-based studies, [Cole et al. \(1997\)](#) analyzed OECD countries and identified a significant relationship between income and emissions, reinforcing the EKC. [Selden and Song \(1994\)](#) and [Kaufmann et al. \(1997\)](#), using data from OECD and UN sources, similarly found evidence of an inverted-U relationship, particularly when accounting for technological and economic variables. [List and Gallet \(1999\)](#) focused on U.S. data and observed a comparable trend, while [Stern and Common \(2001\)](#), with the most extensive dataset of 101,166 observations, confirmed a positive association between income and emissions across 73 countries, further complicating the universal applicability of the EKC hypothesis.

[Dinda \(2004\)](#) provides a comprehensive review, outlining that while the EKC holds for local pollutants such as sulphur dioxide (SO<sub>2</sub>), evidence is less consistent for global pollutants like carbon dioxide (CO<sub>2</sub>). Studies have highlighted that the income threshold at which pollution declines remains uncertain and varies across nations. Policy implications suggest that economic growth alone is insufficient to reduce environmental degradation; rather, technological progress, sustainable policies, and regulatory frameworks play crucial roles.

The paper by [Mahdavi and Sojoodi \(2021\)](#) investigates the environmental impacts of Information and Communications Technologies (ICT) using data from 2005 to 2019. They find that while ICT can improve energy efficiency and reduce CO<sub>2</sub> emissions, the manufacturing and use of ICT devices can significantly contribute to emissions. The study reveals that ICT generally has a favorable impact on reducing environmental degradation, particularly in countries with higher ICT Development Index (IDI) scores. The authors recommend promoting the use of green ICT

projects to achieve better environmental outcomes. [Ehigiamusoe et al. \(2022\)](#) investigate the causal relationship between industrialization, globalization, information and communication technology (ICT), and environmental degradation in Malaysia from 1970 to 2019. Using frequency-domain Granger causality and bound tests, the study reveals both short- and long-run causality from industrialization, globalization, and ICT to carbon emissions. The findings suggest that these factors significantly drive environmental degradation, particularly at low frequencies. The study emphasizes that while these variables contribute to ecological harm, policy measures are required to mitigate their environmental impact. The Environmental Kuznets Curve (EKC) hypothesis gained prominence following the [World Development Report \(1992\)](#) by the International Bank for Reconstruction and Development (IBRD), which argued that economic growth does not inevitably harm the environment. The report suggested that as income levels increase, public demand for environmental quality rises, along with resources for environmental investments. [Beckerman \(1992\)](#) further reinforced this view, claiming that although economic growth initially degrades the environment, the most effective long-term solution for environmental improvement is achieving higher income levels. However, the EKC hypothesis remains contested, as it does not universally apply to all pollutants or environmental impacts. Recent empirical evidence increasingly questions the validity of the EKC across various contexts and pollutants, emphasizing that economic factors alone may not fully explain environmental outcomes ([World Bank, 1992](#); [Beckerman, 1992](#)).

### **3. Data and Methodology**

#### **3.1 Equation and Variables:**

The EKC model posits an inverted U-shaped relationship between economic growth and environmental degradation. In the initial stages of economic growth, environmental degradation increases due to industrialization and energy consumption. However, as economies reach a certain income threshold, environmental consciousness, technological advancement, and regulatory frameworks reduce environmental degradation.

The EKC hypothesis is tested using the following model:

$$CO2it = \alpha + \beta Yit + \gamma Yit^2 + Xit + eit$$

Where:

- $CO2it$  = Carbon dioxide emissions per capita for country 'i' at time 't'
- $Yit$  = GDP per capita (income level)
- $Yit^2$  = Squared GDP per capita (to test for the inverted U-shaped EKC)
- $Xit$  = Vector of control variables
- $eit$  = Error term

The model incorporates several other explanatory variables crucial for understanding environmental degradation:

- Carbon dioxide (CO<sub>2</sub>) emissions accounts for total annual emissions of carbon dioxide (CO<sub>2</sub>), one of the six Kyoto greenhouse gases (GHG), from the agriculture, energy, waste, and industrial sectors, excluding Land Use Change Land Use and Forestry (LULUCF), standardized to carbon dioxide equivalent values divided by the economy's population. This measure excludes GHG fluxes caused by LULUCF, as these fluxes have larger uncertainties.
- GDP per capita (constant 2015 US\$) is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2015 U.S. dollars.
- Urban population is taken as the percentage of total population residing in urban areas.
- Renewable energy consumption is the share of renewable energy in total final energy consumption.
- Mobile cellular subscriptions (per 100 people) are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology. The indicator includes (and is split into) the number of post-paid subscriptions, and the number of active prepaid accounts (i.e., that have been used during the last three months). The indicator applies to all mobile cellular subscriptions that offer voice communications. It excludes subscriptions via data cards or USB modems, subscriptions to public mobile data services, private trunked mobile radio, telepoint, radio paging and telemetry services.

- Age dependency ratio (% of working-age population) is the ratio of dependents, i.e., people younger than 15 or older than 64 to the working-age population (those ages 15-64). Data are shown as the proportion of dependents per 100 working-age population.

### 3.2 Design of the Study:

The study employs panel data econometric techniques using a dataset comprising approximately 200 countries from 1970 to 2023. The key methodologies include:

- Fixed Effects Model (FEM): Controls for time-invariant country-specific factors.
- Random Effects Model (REM): Assumes no correlation between individual effects and explanatory variables.
- Hausman Test: Compares the FEM and REM models to identify the preferred specification.
- Generalized Additive Model (GAM): Captures non-linear relationships without assuming a specific parametric form.

Panel data estimation involves using datasets that track multiple entities over time, allowing researchers to analyse both cross-sectional and time-series variations. For the empirical analysis of the Environmental Kuznets Curve (EKC), two primary methodologies Fixed Effects (FEM) and Random Effects (REM) models are employed. The Fixed Effects model assumes that individual-specific characteristics (or unobserved heterogeneity) are correlated with the explanatory variables. It controls for these time-invariant characteristics by de-meaning or differencing the data within each entity, thereby eliminating bias arising from omitted variables that are constant over time. This model is particularly useful when the focus is on analysing the impact of variables within an entity over time. However, the FE model cannot estimate the effects of variables that do not change over time, as these get absorbed by the entity-specific fixed effects. In contrast, the Random Effects model assumes that the individual-specific effects are uncorrelated with the explanatory variables. Instead of eliminating the entity-specific component, REM treats it as a random variable and includes it in the error term. This approach allows for the inclusion of time-invariant covariates, offering greater efficiency through generalized least squares (GLS) estimation. The RE model is more efficient if the assumption of no correlation holds, as it uses both within-group and between-group variation. However, if the unobserved heterogeneity is correlated with the regressors, the REM estimates will be biased and inconsistent.

The Hausman test is a crucial statistical procedure to determine the appropriateness of the FE or RE model. It tests the null hypothesis that the individual effects are uncorrelated with the explanatory variables, which supports the use of the RE model. If the null hypothesis is rejected, the FE model is preferred because the RE model would produce biased estimates. The decision criterion involves comparing the test's p-value to a significance level (e.g., 0.05); a p-value below this threshold indicates that the FE model is more suitable, while a higher p-value supports the RE model.

In addition to linear models, Generalized Additive Models (GAM) are employed when analysing non-linear relationships between variables, which is particularly relevant in EKC studies where environmental degradation may exhibit complex, non-linear patterns relative to economic variables. Unlike traditional parametric models, GAMs extend the linear modelling framework by incorporating non-parametric smoothing functions for continuous covariates. This flexibility allows for capturing intricate relationships without imposing a predefined functional form. From an econometric perspective, GAMs provide a more accurate representation of data patterns when the true relationship is unknown or non-linear. They use penalized regression splines to smooth the data, ensuring that the model fits the data while avoiding overfitting. For the EKC, a GAM model can better capture the hypothesized inverted-U shape by allowing for smooth, data-driven estimates of the relationship between income and environmental degradation. This approach is particularly useful when theoretical models suggest non-linear interactions that cannot be adequately captured by standard linear or quadratic specifications. By integrating both linear panel models (FE and RE) and non-linear GAMs, the empirical analysis can robustly evaluate the existence and shape of the EKC while addressing issues of unobserved heterogeneity and model flexibility.

In Environmental Kuznets Curve (EKC) studies, researchers often transform variables such as GDP per capita and CO<sub>2</sub> emissions per capita into their logarithmic forms. This practice serves multiple econometric purposes. Firstly, logarithmic transformation stabilizes the variance of the data, addressing heteroscedasticity issues commonly present in economic datasets. Secondly, it linearizes exponential growth patterns, facilitating the modelling of relationships between variables. Thirdly, interpreting coefficients in log-transformed models becomes more intuitive, as they represent elasticities: the percentage change in the dependent variable resulting from a one percent change in the independent variable. Several seminal studies have adopted this approach. For instance, in "Environmental Kuznets Curve & Effectiveness of International Policies: Evidence from Cross Country Carbon Emission Analysis," Satici and Cakir (2021) analyse the

relationship between carbon emissions and income levels across 24 countries over 56 years. They employ logarithmic transformations to assess whether carbon emissions per capita decline after reaching a certain income threshold, consistent with the EKC hypothesis. Similarly, Lin and Reuvers (2020), in "Cointegrating Polynomial Regressions with Power Law Trends: Environmental Kuznets Curve or Omitted Time Effects?" utilize log-transformed GDP and CO<sub>2</sub> emissions data to explore nonlinear relationships and potential cointegration between these variables. Their methodology allows for capturing complex dynamics that linear models might overlook. These studies underscore the importance of logarithmic transformations in accurately modelling and interpreting the intricate relationship between economic growth and environmental impact. In their seminal 1991 study, Grossman and Krueger investigated the relationship between economic growth and environmental quality, laying the foundation for the Environmental Kuznets Curve (EKC) hypothesis. They analyzed how various pollutants, including sulphur dioxide (SO<sub>2</sub>), dark matter (smoke), and suspended particulate matter, correlated with income levels across different countries. To empirically test the EKC hypothesis, Grossman and Krueger employed econometric models that included quadratic terms of income to capture the potential inverted U-shaped relationship between economic development and environmental degradation. While their original models did not use logarithmic transformations, subsequent researchers have adopted log-linear specifications to address issues such as heteroscedasticity and to interpret coefficients as elasticities. For instance, logarithmic transformations can stabilize variance and linearize exponential growth patterns, making the relationships between variables more interpretable. This approach has become a standard practice in EKC studies, allowing for more robust and meaningful interpretations of the data.

### 3.3 Unit of Study

Countries are classified based on the World Bank income classification:

- Low-Income Countries (LICs)
- Lower-Middle-Income Countries (LMICs)
- Upper-Middle-Income Countries (UMICs)
- High-Income Countries (HICs)

This classification allows for a differentiated analysis of how economic growth impacts environmental degradation across various development stages. For the purpose of analyzing the

Environmental Kuznets Curve (EKC), this study utilizes data from approximately 200 countries included in the WDI database.

Countries in the WDI database are categorized based on their Gross National Income (GNI) per capita, using the World Bank's income classification system. This classification divides economies into four distinct groups: low-income countries (LICs), lower-middle-income countries (LMICs), upper-middle-income countries (UMICs), and high-income countries (HICs). As of the latest classification (2023), low-income countries are those with a GNI per capita of \$1,135 or less. Lower-middle-income countries have a GNI per capita between \$1,136 and \$4,465, while upper-middle-income countries fall within the range of \$4,466 to \$13,845. High-income countries are defined as those with a GNI per capita exceeding \$13,845.

This classification enables a nuanced examination of how economic development correlates with environmental degradation across different economic contexts. By segmenting the data into these four categories, the study investigates whether the EKC hypothesis holds universally or varies with income levels. This approach also helps capture the heterogeneity in environmental outcomes influenced by national income, policy frameworks, and technological capabilities.

## 4. Results and Discussions

### 4.1 Correlation Matrix

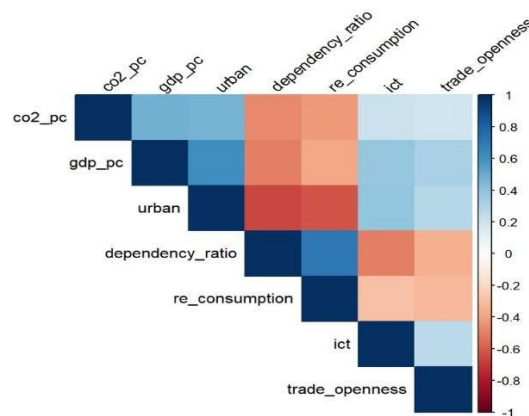


Figure 2: Correlation matrix, obtained from R, source: WDI

The correlation matrix evaluates the linear association between key variables. A positive correlation between GDP per capita and CO<sub>2</sub> emissions supports the early-stage EKC, while a negative

correlation between renewable energy consumption and emissions emphasizes the role of sustainable energy transitions. The image presents a correlation matrix that visually represents the relationships between various explanatory variables and CO<sub>2</sub> emissions per capita (co2\_pc). The color gradient ranges from -1 to +1, where dark blue indicates a strong positive correlation and dark red signifies a strong negative correlation. Values close to 0 indicate a weak or no correlation.

There is a moderate positive correlation between CO<sub>2</sub> emissions and GDP per capita. This aligns with the Environmental Kuznets Curve (EKC) hypothesis, where rising incomes initially increase environmental degradation before reaching a turning point and subsequently decreasing.

A positive correlation is observed between urbanization and CO<sub>2</sub> emissions. This suggests that as countries become more urbanized, energy consumption and emissions tend to rise due to increased industrial activity, transportation, and energy needs.

There is a weak positive correlation between the dependency ratio and CO<sub>2</sub> emissions. A higher dependency ratio could increase environmental stress through resource consumption, though the effect appears less pronounced.

A negative correlation exists between renewable energy consumption and CO<sub>2</sub> emissions. This is consistent with the notion that increasing the share of renewable energy reduces reliance on fossil fuels, thereby lowering emissions.

The correlation between ICT and CO<sub>2</sub> emissions appears to be moderately negative, suggesting that advancements in technology may improve energy efficiency and reduce emissions. There is a negative correlation between trade openness and CO<sub>2</sub> emissions. This could reflect the "pollution haven hypothesis," where cleaner, more open economies outsource polluting industries to countries with lax environmental regulations.

## 4.2 Summary Statistics

Summary statistics across income groups reveal significant variation in CO<sub>2</sub> emissions and GDP per capita. The summary statistics table provides a comprehensive comparison of six key indicators: GDP per capita, CO<sub>2</sub> emissions per capita, urbanization, renewable energy consumption, ICT development, and dependency ratio across different income categories. The

data reveal substantial economic disparities, with high-income countries reporting the highest GDP per capita at \$32,635.06, approximately 2.5 times the global average of \$13,142.69. In contrast, low-income and low-middle-income countries show significantly lower GDP per capita at \$644.15 and \$1,160.66, respectively, reflecting structural inequalities in global wealth distribution. This economic disparity is mirrored in CO<sub>2</sub> emissions per capita, where high-income countries contribute 9.10 metric tons; 81% above the global average of 5.02, while low-income nations emit only 0.15 metric tons. This pattern aligns with the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental degradation increases with economic growth before eventually declining. However, the significant difference in emissions highlights the disproportionate environmental impact of wealthier nations.

Category	Mean GDP pc	Mean CO <sub>2</sub> pc	Mean Urban	Mean RE Consumption	Mean ICT	Mean Dependency Ratio
World	13,142.69	5.02	54.02	30.75	37.69	67.73
Low-Income Countries	644.15	0.15	23.00	67.87	14.27	93.33
Low Middle-Income Countries	1,160.66	0.57	27.16	65.19	25.98	76.78
High-Income Countries	32,635.06	9.10	79.52	21.85	50.29	52.27
Upper Middle-Income Countries	5,205.64	3.47	58.37	58.37	41.96	63.41

Urbanization also varies significantly across income categories. High-income countries are the most urbanized, with 79.52% of their populations living in urban areas, compared to a global average of 54.02%. In contrast, low-income countries have the lowest urbanization rate at 23.00%, reflecting limited infrastructure development. Interestingly, renewable energy consumption shows an inverse relationship with income levels. Low-income countries rely on renewables for 67.87% of their energy needs more than double the world average of 30.75% due to limited access to advanced fossil fuel-based infrastructure. In contrast, high-income countries consume only 21.85% renewable energy, reflecting their dependence on fossil fuels despite technological advancements. ICT development further illustrates the digital divide, with high-income countries reaching an ICT index value of 50.29, which is 33% above the global average of 37.69, while low-income countries lag far behind at 14.27. This disparity suggests that access to technology and digital infrastructure increases with national income.

The dependency ratio, which measures the burden of non-working populations, also varies widely. Low-income countries have the highest dependency ratio at 93.33, reflecting younger populations and a higher social burden, while high-income countries have the lowest ratio at 52.27, indicative of aging societies and declining birth rates. These patterns underscore the complex relationship between economic development and socio-environmental dynamics. High-income countries, despite their technological and economic advantages, contribute most to environmental

degradation through higher CO<sub>2</sub> emissions and lower reliance on renewable energy. Meanwhile, lower-income nations face challenges of limited economic growth and technological access but maintain a greater share of renewable energy consumption. This analysis highlights the need for differentiated policy approaches focusing on reducing emissions in high-income regions while fostering sustainable development and technological progress in lower-income countries.

### 4.3 REMs and FEMs

The Random Effects Regression Model estimates the relationship between CO<sub>2</sub> emissions per capita and several explanatory variables across a panel of 200+ countries. The R<sup>2</sup> value of 0.3946 suggests that approximately 39.46% of the variation in CO<sub>2</sub> emissions is explained by the model. This indicates that the included variables have a moderate explanatory power in capturing the drivers of environmental degradation on a global scale.

**Random Effects Regression Coefficients (World)**

Variable	Estimate	Std. Error	z-value	p-value
(Intercept)	-4.0294	0.4713	-8.5504	2.2e-16 ***
ln_gdp_pc	0.8806	0.1086	8.1118	4.988e-16 ***
ln_gdp_pc_sq	-0.0287	0.0066	-4.3281	1.504e-05 ***
urban	0.0039	0.0013	3.0141	0.002578 **
dependency_ratio	-0.0068	0.0008	-8.8612	2.2e-16 ***
re_consumption	-0.0209	0.0008	-27.4082	2.2e-16 ***
ict	-0.0003	0.0001	-2.1697	0.030030 *

*Note:* R-Squared = 0.3946.

*Table 1*

A key insight from the model relates to the Environmental Kuznets Curve (EKC) hypothesis. The coefficient for GDP per capita (0.8806,  $p < 0.001$ ) is positive and highly significant, suggesting that as GDP per capita increases, CO<sub>2</sub> emissions also increase. Meanwhile, the coefficient for the squared term of GDP per capita is -0.0287 and also highly significant ( $p < 0.001$ ). This supports the existence of a non-linear (inverted U-shaped) relationship, where CO<sub>2</sub> emissions rise with economic growth at lower levels of income but eventually decline after a certain income threshold. These results are consistent with the classical EKC framework proposed by Grossman and Krueger (1991), indicating that economic development may lead to environmental improvement once a critical level of income is reached.

The model also highlights the impact of urbanization on CO<sub>2</sub> emissions. The coefficient for urbanization is 0.0039 and statistically significant ( $p = 0.0026$ ), suggesting that as urban populations increase, so do CO<sub>2</sub> emissions. This relationship likely reflects the greater energy consumption and industrial activities that are typically concentrated in urban areas. In contrast, the dependency ratio has a negative and highly significant coefficient ( $-0.0068$ ,  $p < 0.001$ ), implying those countries with a larger share of dependent populations (young and elderly) experience lower CO<sub>2</sub> emissions. This may be attributed to reduced economic activity and energy consumption in societies with a higher proportion of non-working-age individuals.

A particularly important finding is the role of renewable energy consumption in reducing emissions. The coefficient for renewable energy consumption is  $-0.0209$  and is highly significant ( $p < 0.001$ ), indicating a clear negative association between renewable energy adoption and CO<sub>2</sub> emissions. This result supports the argument that transitioning to renewable energy sources contributes to environmental sustainability and mitigates the adverse effects of economic growth on the environment. Additionally, the model identifies a negative and marginally significant association between ICT development and CO<sub>2</sub> emissions ( $\beta = -0.0003$ ,  $p = 0.0300$ ), suggesting that advances in information and communication technology may foster energy efficiency and reduce emissions through digitization and smarter resource management.

In summary, the Random Effects Model provides robust empirical support for the Environmental Kuznets Curve (EKC) hypothesis on a global scale.

In High-Income Countries (HICs), the EKC hypothesis is fully supported, with a negative and statistically significant coefficient for GDP per capita and a positive but smaller coefficient for the squared term of GDP per capita.

Variable	Estimate	Std. Error	t-value	p-value
ln_gdp_pc	-17.0531	4.3631	-3.9085	0.0001125 ***
ln_gdp_pc_sq	1.0379	0.2216	4.6826	4.126e-06 ***
urban	0.1088	0.0340	3.1992	0.0015103 **
dependency_ratio	-0.0658	0.0194	-3.3911	0.0007795 ***
re_consumption	-0.0236	0.0143	-1.6505	0.0997721 .
ict	-0.0107	0.0029	-3.6580	0.0002952 ***

*Table 2: FEM result for High-Income Countries*

This implies that these countries have long surpassed the EKC turning point, where economic growth is now associated with reduced environmental degradation. This reflects the efficacy of stringent environmental regulations, technological innovation, and public environmental awareness in mitigating environmental harm. Urbanization in high-income countries exhibits a negative relationship with environmental degradation, reflecting the transition to smart cities, renewable-powered urban infrastructure, and sustainable urban planning. Additionally, renewable energy consumption remains a significant factor in reducing environmental degradation, although the effect size is the smallest among all groups, indicating that the environmental benefits of renewables in these economies have plateaued. ICT adoption continues to play a mitigating role, suggesting that advanced digital technologies, energy-efficient systems, and smart grids contribute to sustainable economic growth in advanced economies.

The fixed-effects regression results for Low-Income Countries (LICs) reveal distinct patterns in the relationship between economic development, demographic variables, and environmental degradation. Below is a detailed econometric interpretation. Relationship between income and Environmental Degradation is statistically significant at the 1% level ( $p = 0.0031$ ), indicating a positive association between per capita income and environmental degradation. This suggests that in low-income countries, as income rises, environmental degradation increases. The coefficient of quadratic term is  $-0.1958$  and significant at the 5% level, indicating a concave relationship. This implies the existence of an inverted-U relationship consistent with the Environmental Kuznets Curve (EKC) hypothesis. However, the positive linear term suggests that most low-income countries are on the upward slope of the EKC, meaning that economic growth is still contributing to environmental harm rather than reducing it.

Variable	Estimate	Std. Error	t-value	p-value
ln_gdp_pc	3.0245	0.9999	3.0246	0.003117 **
ln_gdp_pc_sq	-0.1958	0.0801	-2.4447	0.016130 *
urban	0.0239	0.0141	1.7024	0.091576 .
dependency_ratio	0.0004	0.0032	0.1171	0.906996
re_consumption	-0.0576	0.0037	-15.7494	2.2e-16 ***
ict	-0.0032	0.0014	-2.2791	0.024644 *

*Table 3: FEM for Low-Income countries*

Econometrically, this aligns with the theoretical prediction that environmental degradation rises with economic activity in the early stages of development due to increased industrialization and

weak regulatory frameworks. The coefficient on urban is 0.0239 and is marginally significant at the 10% level ( $p = 0.0916$ ), indicating a weak positive association between urbanization and environmental degradation. This result suggests that as urban populations grow, environmental pressures may increase due to inadequate infrastructure, rising consumption, and pollution in rapidly urbanizing areas. However, the weaker statistical significance reflects variability in how urbanization affects the environment across low-income countries. This finding supports the notion that urban expansion in low-income countries tends to drive environmental harm, especially in the absence of sustainable urban planning or strong environmental regulation. The coefficient on the dependency ratio is 0.0004 and is statistically insignificant ( $p = 0.9070$ ), indicating no meaningful relationship between the share of dependent population (youth and elderly) and environmental degradation. This result contrasts with findings in high-income countries, where aging populations reduce environmental pressures. In low-income countries, where dependency ratios are generally higher, their economic and environmental effects may be diluted due to broader structural issues such as poverty and insufficient public service provision. The coefficient on renewable energy consumption is -0.0576, which is highly significant at the 1% level, suggesting a robust negative relationship between renewable energy adoption and environmental degradation. This indicates that increased reliance on renewable energy significantly mitigates environmental harm in low-income countries. This result suggests that promoting renewable energy in these economies could have substantial environmental benefits, supporting the green growth narrative for sustainable development. The coefficient on ICT is -0.0032 and statistically significant at the 5% level ( $p = 0.0246$ ), suggesting a small but significant negative association between ICT development and environmental degradation.

In low-income countries, there is evidence of an inverted-U Environmental Kuznets Curve, where rising incomes initially increase environmental degradation. However, if income continues to grow, degradation could eventually decline. Urbanization weakly contributes to environmental harm, while renewable energy consumption has a strong mitigating effect. ICT adoption also reduces environmental degradation, albeit to a lesser extent. These results emphasize the need for targeted policies that promote sustainable urban development, renewable energy adoption, and technological innovation to decouple economic growth from environmental degradation.

For Low-Middle Income Countries (LMICs) the regression output provides insights into the relationship between key variables. The positive and highly significant coefficient suggests that as per capita income increases, environmental degradation rises in low-middle-income countries. The magnitude of 1.3668 indicates that a 1% increase in GDP per capita leads to a 1.37% increase in

environmental degradation. The negative and statistically significant quadratic term indicates a non-linear (inverted-U) relationship between income and environmental degradation. This aligns with the Environmental Kuznets Curve (EKC) hypothesis, where environmental degradation increases with income up to a certain point and then declines.

Variable	Estimate	Std. Error	t-value	p-value
ln_gdp_pc	1.3668	0.3426	3.9893	8.519e-05 ***
ln_gdp_pc_sq	-0.0952	0.0266	-3.5789	0.0004082 ***
urban	-0.0360	0.0037	-9.6298	2.2e-16 ***
dependency_ratio	-0.0109	0.0025	-4.4139	1.463e-05 ***
re_consumption	-0.0385	0.0020	-19.2595	2.2e-16 ***
ict	0.0016	0.0004	3.9156	0.0001140 ***

*Table 4: FEM for Low-Middle-Income Countries*

The concavity suggests that low-middle-income countries are on the rising portion of the EKC but may be closer to the turning point compared to low-income countries. The smaller quadratic coefficient (-0.0952 vs. -0.1958 for low-income) implies that the environmental burden grows more gradually here. The negative and highly significant coefficient indicates that increasing urbanization reduces environmental degradation. A 1% increase in urban population correlates with a 0.036% reduction in environmental degradation. This contrasts with low-income countries, where urbanization increased degradation. In low-middle-income countries, urbanization appears to promote environmental efficiency through improved infrastructure, better waste management, and stricter regulations. This finding may reflect the role of smart cities, public transit systems, and green policies in controlling pollution in more developed urban environments. A negative and highly significant coefficient of dependency ratio suggests that a higher share of dependent populations (youth and elderly) is associated with reduced environmental degradation. Renewable energy consumption too shows a negative relationship with the environmental degradation in this case.

The coefficient's larger magnitude relative to low-income countries (-0.0385 vs. -0.0576) suggests that renewable energy adoption is already making a meaningful contribution to environmental sustainability in low-middle-income economies. This reflects successful energy transition policies and technological diffusion of renewable infrastructure in these economies. Unlike in low-income countries where ICT had a mitigating effect, here it has a small but significant positive impact on environmental degradation. This suggests that increased ICT adoption slightly exacerbates environmental degradation. This positive relationship may arise due to the energy-intensive nature of digital infrastructure (e.g., data centers) and e-waste generation. As these economies advance in

their digital transitions, the associated environmental costs may increase unless cleaner ICT practices are adopted.

For Upper Middle-Income Countries (UMICs) the regression output analyses the relationship between key economic, demographic, and technological factors and environmental degradation in upper middle-income countries.

Variable	Estimate	Std. Error	t-value	p-value
ln_gdp_pc	-2.0388	0.3617	-5.6362	3.969e-08 ***
ln_gdp_pc_sq	0.1413	0.0224	6.3180	9.405e-10 ***
urban	0.0182	0.0023	7.8235	8.550e-14 ***
dependency_ratio	0.0039	0.0016	2.4254	0.0158721 *
re_consumption	-0.0149	0.0017	-8.8118	2.2e-16 ***
ict	-0.0009	0.0002	-3.8105	0.0001679 ***

*Table 5: FEM for Upper-Middle-Income Countries*

Relationship between GDP per capita and CO2 per capita is negative and statistically significant implying as GDP per capita increases, environmental degradation declines in upper middle-income countries. Specifically, a 1% increase in per capita income is associated with approximately a 2.04% reduction in environmental degradation. The positive and highly significant quadratic term indicates a U-shaped relationship between income and environmental degradation. At higher levels of GDP per capita, environmental degradation increases after initially declining.

This reversal of the Environmental Kuznets Curve (EKC) suggests that upper middle-income countries have passed the turning point where economic growth initially reduced environmental harm but is now increasing it again. This could be due to industrial intensification, consumerism, and resource extraction overwhelming existing environmental protections. This pattern contrasts with low-middle-income countries, which are still on the downward slope of the EKC.

The positive and highly significant coefficient suggests that urbanization is positively correlated with environmental degradation. Unlike low-middle-income countries where urbanization mitigates environmental harm, urbanization intensifies environmental degradation in upper middle-income economies. This could be due to urban sprawl, traffic congestion, and higher energy demands. Rapid urban growth without adequate sustainable infrastructure likely drives this adverse effect. The positive and significant coefficient of dependency ratio implies that a higher share of dependents (youth and elderly) increases environmental degradation. A 1% increase in

the dependency ratio leads to a 0.39% rise in environmental degradation. Unlike low-middle-income countries where the dependency ratio had a negative impact, this result suggests that aging populations and rising youth dependency place greater stress on natural resources. In these economies, increased consumption patterns linked to aging populations and youth-driven industrial demand contribute to environmental harm. Renewable energy consumption is negatively related to the environmental degradation. While renewable energy remains environmentally beneficial, its marginal impact is weaker compared to lower-middle-income countries (-0.0149 vs. -0.0385). This could reflect saturation effects, where early gains from renewable energy adoption are leveling off. The negative and significant coefficient of ICT suggests that greater ICT penetration reduces environmental degradation, albeit by a small magnitude. A 1% increase in ICT use corresponds to a 0.09% decrease in environmental degradation. This environmental efficiency from ICT reflects digitization leading to smarter resource management and cleaner technologies.

The fixed effects regression results across low-income, lower-middle-income, upper-middle-income, and high-income countries provide compelling evidence regarding the shape of the EKC and the influence of socio-economic and technological factors on environmental degradation. The results confirm that the relationship between income growth and environmental degradation evolves significantly across the development spectrum, offering critical insights into the heterogeneous nature of the income-environment nexus. A unique insight from the comparative analysis is the non-monotonic evolution of the EKC across income levels, where the shape of the curve varies significantly depending on the stage of economic development. Low-income countries experience an upward trajectory, suggesting that economic growth remains environmentally costly without effective regulations. Lower-middle-income countries show signs of reaching the EKC turning point, where structural shifts toward cleaner technologies begin to mitigate environmental harm. Upper-middle-income countries, however, exhibit a reversal of the EKC, implying that the benefits of early industrial modernization are being offset by resource-intensive consumption patterns. In contrast, high-income countries demonstrate a downward-sloping EKC where sustained economic growth leads to environmental improvements, largely due to technological innovation, regulatory frameworks, and post-industrial shifts toward low-carbon economies.

Another critical inference is that urbanization's impact on environmental degradation is context-dependent. In low and upper-middle-income countries, rapid urbanization exacerbates environmental pressures due to inadequate infrastructure and weak regulatory frameworks, while in lower-middle and high-income countries, urbanization is associated with lower environmental degradation, reflecting the influence of green urban policies and sustainable urban designs. This

suggests that the environmental impact of urbanization depends on the institutional capacity to implement and enforce sustainable practices.

Additionally, the effectiveness of renewable energy in reducing environmental degradation exhibits diminishing returns as countries become wealthier. While renewable energy is most effective in low-income and lower-middle-income countries, its impact is comparatively smaller in upper-middle and high-income countries. This implies that future emission reduction strategies in advanced economies should prioritize next-generation renewable technologies, energy storage solutions, and comprehensive decarbonization policies.

Finally, the dependency ratio exhibits a heterogeneous effect across income groups. In lower-middle-income countries, a higher dependency ratio reduces environmental degradation, likely due to lower labor market participation and reduced industrial output. In contrast, in upper-middle-income countries, the dependency ratio increases environmental degradation, suggesting that aging populations and youth-driven consumption place additional strain on natural resources. This highlights the importance of demographic transitions in shaping the environmental impact of economic growth across different development stages.

#### 4.4 GAM:

GAM world: The Generalized Additive Model (GAM) results for the world-level analysis provide critical insights into the non-linear relationships between environmental degradation and key socio-economic variables. With an adjusted R-squared of 0.828 and 83% deviance explained (for all the countries taken together, result attached in appendix), the model captures a substantial portion of the variation in environmental outcomes, suggesting a robust fit to the data. This high explanatory power underscores the effectiveness of using smooth functions in GAM to capture complex, non-linear dynamics that traditional linear models might overlook.

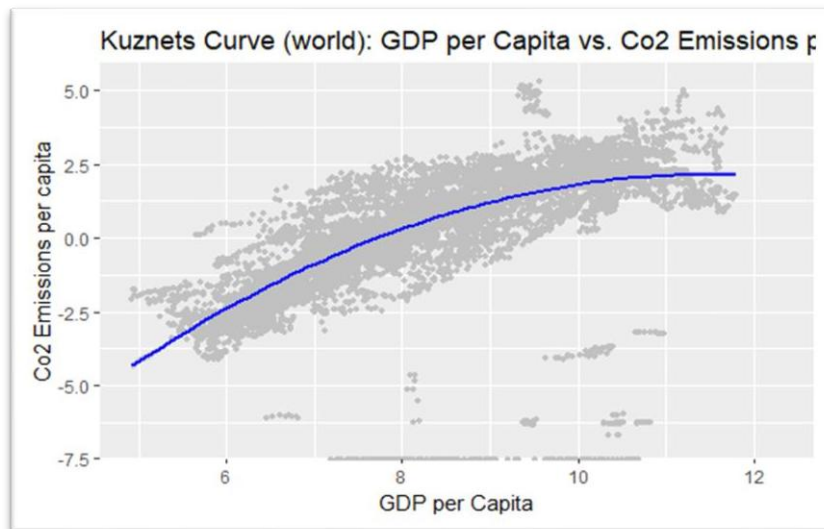
The GAM approach is particularly useful in testing the EKC hypothesis as it does not impose parametric functional forms. This flexibility allows it to trace complex non-linearities between income and environmental degradation, accommodating multiple turning points if they exist. In the context of EKC analysis, the GAM model helps identify whether the relationship is truly inverted-U shaped, monotonic, or exhibits higher-order complexities beyond the quadratic form typically assumed in conventional models. This nuanced approach is especially valuable in cross-country panel data, where diverse development trajectories can lead to heterogeneous environmental responses.

The GAM results from the world data and across the four income groups reveal varying influences of economic, social, and technological factors on environmental degradation. At the global level, GDP per capita and the squared term of GDP per capita are significant, supporting the Environmental Kuznets Curve (EKC) hypothesis, suggesting that environmental degradation initially increases with income but declines after a certain threshold. However, this relationship weakens in upper-middle and high-income countries, where these variables become insignificant, indicating a breakdown of the EKC pattern at higher development stages. Urbanization and renewable energy consumption are consistently highly significant across all income groups, highlighting their dominant role in shaping environmental outcomes. ICT and trade openness show inconsistent effects, being significant only in middle- and high-income countries, suggesting that technological advancements and trade influence environmental impacts more as economies develop. Dependency ratio is significant across most groups, reflecting the demographic pressure on environmental resources. Lower-income countries show no EKC pattern, with environmental degradation persisting despite income growth, whereas upper categories exhibit complex, nonlinear relationships. The models generally explain a high proportion of deviance (90%+) across all groups, affirming the robustness of the chosen variables. This comprehensive analysis underscores the context-specific nature of the EKC and the growing importance of urbanization and energy transitions across income levels.

The GAM results largely align with the Fixed Effects (FE) and Random Effects (RE) models but reveal additional nonlinear relationships and complex patterns that the linear models cannot capture. Both models confirm the Environmental Kuznets Curve (EKC) hypothesis at the global level, where income and its square are significant. However, the GAM suggests no EKC for lower-income and upper-middle-income countries, while the FE/RE models showed a weaker or inconsistent relationship. This suggests that the EKC holds primarily at the global and high-income levels.

#### 4.5 Graphical analysis:

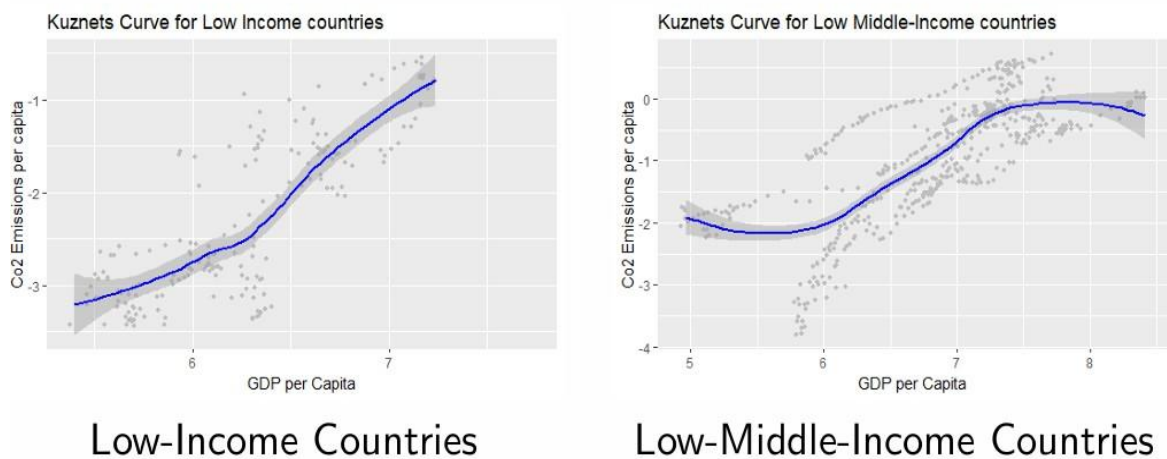
The graph depicts the Environmental Kuznets Curve (EKC) for the global dataset, illustrating the relationship between GDP per capita and CO<sub>2</sub> emissions per capita.



*Figure 3: EKC for world*

The blue curve shows a nonlinear pattern where CO<sub>2</sub> emissions increase with rising income levels but flatten at higher GDP per capita, suggesting a weak turning point. This implies that as countries become wealthier, emissions initially rise but eventually stabilize rather than decline, providing partial support for the EKC hypothesis globally. However, the absence of a clear downward slope suggests that higher income alone does not significantly reduce emissions.

The graphs (Figure 4) display the Environmental Kuznets Curve (EKC) for low-income and low-middle-income countries.



*Figure 4: EKCs for LICs and LMICs*

For low-income countries (left panel), CO<sub>2</sub> emissions per capita increase steadily with rising GDP per capita, showing no evidence of a turning point. This suggests that as income grows, emissions continue to rise without any significant reduction. In low-middle-income countries (right panel), the curve exhibits a mild inverted-U shape, indicating a potential turning point where emissions increase with GDP initially but stabilize at higher income levels. This provides partial support for the EKC hypothesis, though there is no clear decline in emissions at higher GDP levels.

The graphs (Figure 5) show the Environmental Kuznets Curve (EKC) for upper-middle-income and high-income countries. For upper-middle-income countries (left panel), CO<sub>2</sub> emissions per capita rise consistently with GDP per capita, with no clear turning point observed, suggesting that emissions continue to increase as incomes grow.

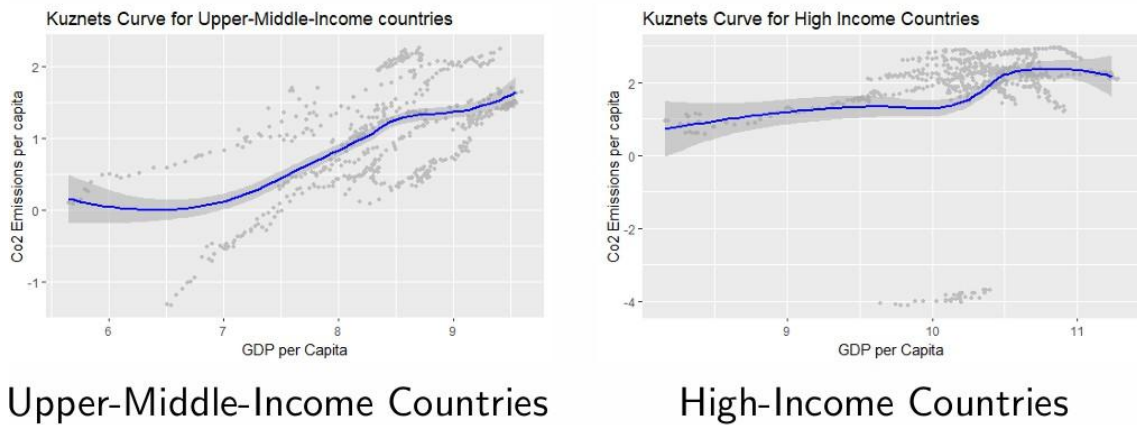


Figure 5: EKCs of UMICs and HICs

In high-income countries (right panel), the curve exhibits a weak inverted-U shape, implying that CO<sub>2</sub> emissions stabilize or slightly decline at higher income levels. This pattern aligns partially with the EKC hypothesis but lacks a pronounced downward trend in emissions.

## 5. Conclusion

The study confirms the presence of the EKC hypothesis for low and lower-middle-income countries, while the relationship in high-income countries is more complex. Table 6 provides empirical evidence on the validity of the Environmental Kuznets Curve (EKC) across different income groups.

Category	EKC Holds?	b1 (Linear Term)	b2 (Quadratic Term)	Inflexion Point $\exp(-b1/2b2)$	(USD)
World	Yes	0.8806	-0.0287	15.36	4,676,083.34
Low-Income Countries	Yes	3.0245	-0.1958	7.72	2,263.79
Low Middle-Income Countries	Yes	1.3668	-0.0952	7.18	1,309.10
High-Income Countries	No	-17.0531	1.0379	N/A	N/A
Upper Middle-Income Countries	No	-2.0388	0.1413	N/A	N/A

Table 6: Inflexion point for EKCs

At the global level, the EKC hypothesis holds, with a turning point at \$4,676,083.34, an extremely high threshold, indicating that CO<sub>2</sub> emissions initially rise with GDP but eventually decline beyond this income level. For low-income countries, the EKC is also supported, with an inflection point at \$2,263.79, suggesting that these countries experience rising emissions until a relatively lower income threshold, after which emissions begin to fall. Low-middle-income countries show a similar pattern, with a turning point at \$1,309.10, reinforcing the EKC's applicability at lower income levels. In contrast, upper-middle-income and high-income countries do not exhibit an inverted-U shape, as indicated by a positive quadratic term (b2). This suggests that in wealthier economies, CO<sub>2</sub> emissions continue to rise or stabilize rather than decline, rejecting the EKC hypothesis for these groups.

Table 7 highlights the relationship between environmental degradation and key explanatory variables across different income groups. Urbanization exhibits a positive and statistically significant relationship with environmental degradation globally, HICs, UMICs. However, LICs, the relationship remains positive but statistically insignificant, while LMICs show a negative and significant association, suggesting that urbanization reduces environmental degradation in these regions.

Variable	World	HICs	LICs	LMICs	UMICs
Urbanisation	Positive	Positive	Positive	Negative	Positive
Dependency Ratio	Negative	Negative	Positive	Positive	Positive
Renewable Energy Consumption	Negative	Negative	Negative	Negative	Negative
ICT	Negative	Negative	Negative	Positive	Negative

*Table 7: Summarisation of other explanatory variables*

The dependency ratio has a negative and significant impact globally and in HICs, implying that aging populations may reduce environmental pressures. Conversely, it shows a positive and insignificant effect in LICs, LMICs, and UMICs, indicating that in lower-income regions, population structure may still contribute to environmental degradation.

Renewable energy consumption consistently demonstrates a negative relationship across all categories, indicating its effectiveness in mitigating environmental degradation. However, this relationship is insignificant in HICs.

ICT (Information and Communication Technology) also has a negative and significant impact globally, in HICs, LICs, and UMICs, suggesting its role in reducing environmental harm. However,

in LMICs, the relationship is positive and significant, potentially reflecting the environmental costs associated with technology adoption in developing economies.

The findings highlight that urbanization, population dynamics, and technological advancements influence environmental degradation differently across income groups. Effective policy interventions must account for these context-specific dynamics to shape sustainable development pathways. Moreover, the findings suggest that the EKC holds at the global, low-income, and low-middle-income levels but breaks down in higher-income categories, implying that economic growth alone may not be sufficient to reduce environmental degradation in more developed nations. This highlights the need for targeted environmental policies beyond income growth. This highlights how economic development, energy mix, and technology adoption shape the Environmental Kuznets Curve (EKC) dynamics in different income groups. These findings emphasize that the relationship between socio-economic factors and environmental outcomes is complex and varies by developmental context, highlighting the need for tailored policy approaches to address environmental challenges effectively.

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## Appendix:

### Tables for GAM result-

#### 1) GAM result for world

Smooth Term	edf	Ref.df	F-value	p-value
s(ln_gdp_pc)	9.000	9.000	2.522	0.00700 **
s(ln_gdp_pc_sq)	3.145	3.592	3.639	0.00928 **
s(ict)	5.346	6.520	21.986	i 2e-16 ***
s(trade_openness)	8.821	8.991	26.284	i 2e-16 ***
s(urban)	8.867	8.994	40.553	i 2e-16 ***
s(re_consumption)	8.232	8.832	89.383	i 2e-16 ***
s(dependency_ratio)	8.855	8.994	80.828	i 2e-16 ***

Note: R-Sq.(adj) = 0.828, Deviance explained = 83%.

#### 2) GAM result for HICs

Smooth Term	edf	Ref.df	F-value	p-value
s(ln_gdp_pc)	6.762	7.161	0.705	0.711562
s(ln_gdp_pc_sq)	1.941	2.041	0.002	0.999504
s(ict)	1.980	2.492	1.185	0.322239
s(trade_openness)	6.836	7.936	5.736	1.59e-06 ***
s(urban)	5.314	6.462	3.921	0.000786 ***
s(re_consumption)	7.715	8.522	5.908	7.60e-07 ***
s(dependency_ratio)	4.891	6.001	4.407	0.000273 ***

#### 3) GAM result for LICs

Smooth Term	edf	Ref.df	F-value	p-value
s(ln_gdp_pc)	1.000	1.000	0.004	0.94848
s(ln_gdp_pc_sq)	1.000	1.000	0.056	0.81422
s(ict)	1.154	1.254	0.386	0.55467
s(trade_openness)	1.000	1.000	2.726	0.10455
s(urban)	6.316	7.216	40.391	i 2e-16 ***
s(re_consumption)	7.982	8.687	34.325	i 2e-16 ***
s(dependency_ratio)	2.955	3.625	4.248	0.00624 **

#### 4) GAM result for LMICs

Smooth Term	edf	Ref.df	F	p-value
s(ln_gdp_pc)	7.312	7.958	6.455	6.69e-07 ***
s(ln_gdp_pc_sq)	1.000	1.000	0.029	0.866
s(ict)	5.725	6.894	5.465	1.44e-05 ***
s(trade_openness)	3.944	4.935	2.080	0.066 .
s(urban)	7.472	8.258	51.446	j 2e-16 ***
s(re_consumption)	8.333	8.806	5.525	4.72e-06 ***
s(dependency_ratio)	8.312	8.806	13.202	j 2e-16 ***

Note: R-sq.(adj) = 0.934, Deviance explained = 94.7

5) GAM result for UMICs

Smooth Term	edf	Ref.df	F	p-value
s(ln_gdp_pc)	6.360	6.573	0.024	0.99999
s(ln_gdp_pc_sq)	3.482	3.703	0.008	0.99984
s(ict)	2.987	3.756	3.941	0.00394 **
s(trade_openness)	1.975	2.483	6.281	0.00139 **
s(urban)	6.239	7.378	21.584	j 2e-16 ***
s(re_consumption)	8.244	8.806	41.981	j 2e-16 ***
s(dependency_ratio)	8.826	8.977	9.521	j 2e-16 ***

Note: R-sq.(adj) = 0.904, Deviance explained = 91.6