Panel Analysis of Environmental Kuznets Curve Hypothesis in South Korea

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The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between economic growth and environmental quality, where pollution initially increases with income but decreases as economies mature. This study evaluates the validity of the EKC in South Korea, focusing on the relationship between Gross Regional Domestic Product (GRDP) per capita and emissions of air pollutants, including NOx, CO, PM10, and PM2.5, across 16 metropolitan and provincial regions. A panel analysis of random effects was employed to model air pollutant emissions as quadratic functions of GRDP per capita, incorporating GDP squared to test for the inverted U-shaped curve. Historical data from multiple regions were analyzed to capture regional variations in pollution levels and their alignment with the EKC hypothesis. The results reveal mixed evidence for the EKC hypothesis in South Korea. While some pollutants and regions exhibit the characteristic inverted U-shape, others deviate due to industrial activity and urbanization. These findings highlight the influence of additional variables, including industrial specialization and population density, on pollution trends. The study underscores the limitations of the EKC as a universal model, emphasizing the need for more complex frameworks that incorporate region-specific and pollution-specific factors. This research provides valuable insights into South Korea's environmental trajectory, guiding policymakers to design tailored strategies for sustainable economic growth and improved air quality.

Keywords: Environmental Kuznets Curve, air pollution, South Korea, economic growth, sustainable development, panel analysis.

Introduction

Access to clean air, recognized by the United Nations as a fundamental human right, is essential for public health and well-being[1]. Despite this recognition, clean air is not universally accessible, with significant disparities evident across and within nations. Socioeconomic factors, political will, and resource allocation influence air quality equity. Globally, air pollution is a leading cause of mortality, responsible for approximately 7 million deaths annually, with 90 percent of these deaths occurring in low- and middle-income countries. Southeast Asia and the Western Pacific bear the brunt of these fatalities, highlighting the intersection of environmental inequality and economic development. This inequality persists within continents, with impoverished regions consistently experiencing poorer air quality compared to wealthier areas, as evidenced by disparities in PM2.5 levels across Europe.

Air pollution is defined as alterations in natural air composition due to the introduction of chemicals or biological agents that can be harmful at high levels[2]. Despite worldwide efforts to enhance air quality, air pollution remains a substantial cause of mortality, accounting for approximately 7 million deaths annually[3]. However, these fatalities are not evenly distributed globally. A 2016 World Health Organization study revealed that 90 percent of air pollution-related deaths occur in low- to middle-income countries, particularly in developing regions. Additionally, nearly two-thirds of these deaths were concentrated in Southeast Asia and the Western Pacific[4]. Developing nations often prioritize economic growth and industrialization, leaving fewer resources available for addressing air pollution and resulting in less stringent regulations.

Air quality disparities exist not only between continents but also within them. For instance, research by the European Environment Agency examined fine particulate matter (PM2.5, defined as particles with a diameter of 2.5 micrometers or less) in affluent versus impoverished areas of Europe. Between 2007 and 2020, both areas experienced a steady reduction in fine particulate matter levels. However, a consistent positive ratio emerged when comparing PM2.5 levels in poorer regions to wealthier ones, indicating a persistent, slightly increasing disparity in air quality[5].

The disparity in air quality illustrates the complex relationship between economic development and environmental degradation. While poorer regions face higher pollution levels due to weaker regulations and limited resources, economic growth influences pollution trends in intricate ways. The Environmental Kuznets

Curve (EKC) hypothesis provides a framework to explore this relationship, suggesting an inverted U-shaped relationship between economic growth and environmental quality[6]. However, the universality of the EKC is contested, and its applicability varies by pollutant and context. With its dynamic economic growth and regional disparities, South Korea presents a compelling case for testing the EKC hypothesis to understand the interplay between development and air pollution.

The current study uses historical data to verify the EKC hypothesis within South Korea. Economic development and air pollution levels vary across different regions of South Korea. By employing panel analysis, this research examines the validity of the hypothesized inverted U-shape curve, modeled as a quadratic function of GRDP per capita with air pollutant emissions as an outcome. Emissions of critical pollutants—CO, NOx, PM2.5, and PM10—will be analyzed independently.

The findings will inform policymakers and stakeholders about the relationship between economic growth and environmental sustainability, guiding targeted interventions to improve air quality while fostering sustainable development.

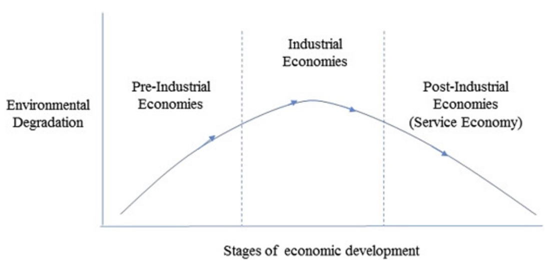

Fig. 1 The Environmental Kuznets Curve

The study's objectives are as follows:

1. To assess the validity of the Environmental Kuznets Curve (EKC) hypothesis in South Korea.
2. To analyze the relationship between Gross Regional Domestic Product (GRDP) per capita and emissions of critical pollutants (CO, NOx, PM2.5, PM10).
3. To examine regional variations in pollution trends and identify key factors influencing these trends.
4. To provide insights to guide policies for balancing economic growth with environmental sustainability.

The Environmental Kuznets Curve (EKC) hypothesis underpins this study, positing an inverted U-shaped relationship between economic growth and environmental degradation. This framework extends Simon Kuznets's original observation on income inequality and is adapted to analyze environmental trends. By modeling air pollution as a quadratic function of GRDP per capita, this research tests the applicability of the EKC in South Korea. The framework is further expanded to incorporate additional variables, such as industrial activity and urbanization, to account for the complex interplay between economic and environmental factors.

The present study seeks to test the validity of the EKC as a framework to explain the relationship between economic growth and environmental degradation. However, the EKC concept remains contentious, especially when examining different pollutants and regions. For example, research on sulfur emissions presents conflicting results, highlighting the complexity and variability of the EKC hypothesis.

Hiroyuki Taguchi analyzed sulfur and carbon emissions across Asia using a reduced-form equation to evaluate per capita emissions concerning GDP per capita and various external factors[7]. The latter degree of development (exogenously economy-specific factors that affect emissions (f_i) was included in the analysis. The findings indicated a U-shaped relationship for carbon emissions but an inverted U-shaped EKC pattern for sulfur emissions. Taguchi proposed that this difference could be due to sulfur's classification as a local pollutant, which tends to be more strictly regulated than global carbon. Furthermore, Taguchi identified a Revised EKC scenario for sulfur emissions, with reduced emission levels observed in advanced stages of urban development.

$$\mathrm{EMS}_{it} = \alpha_0 + \alpha_1 \mathrm{GDP}_{it} + \alpha_2 \mathrm{GDP}_{it}^2 + \alpha_3 \mathrm{LAC}_{it} + \alpha_4 \mathrm{EMS}_{it-1} + \alpha_5 f_i + e_{it} \quad (1)$$

Where:

- EMS_{it} is the measure of per capita emissions of sulfur or carbon for the economy i at time t.
- α_0 is the intercept of the equation, representing the base level of emissions when all other variables are zero.
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are the coefficients corresponding to each independent variable.
- GDP_{it} is the GDP per capita of the economy i at time t.
- LAC_{it} represents the "later development" factor, specifically the ratio GDP_{it} to the maximum GDP per capita among the considered economies in that year. A lower LAC means later development.
- EMS_{it-1} is the one-period lag of emissions, capturing persistence in emission levels.
- f_i denotes exogenously economy-specific factors affecting emissions (e.g., climate, geography, and energy resources).
- e_{it} is the error term.

In contrast, Soo Jung Kim, Tae Yong Jung, and Sung Jin Kang found no support for an EKC relationship for sulfur oxides in their study of South Korean metropolitan regions[8]. Despite using robust models like fixed effects, random effects, and the System Generalized Method of Moments (GMM), sulfur oxides showed no inverted U-shape or similar trajectory under any model, suggesting that sulfur levels may have stabilized due to effective regulatory policies already in place. This study thus highlights that while other pollutants may still align with the EKC, sulfur emissions in South Korea no longer follow this trend, questioning the universality of the EKC for all pollutants and regulatory environments.

$$\ln E_{i,t} = \alpha + \beta_0 \ln E_{i,t-1} + \beta_1 \ln Y_{i,t} + \beta_2 (\ln Y_{i,t})^2 + \beta_3 X_{i,t} + u_i + \theta_t + e_{i,t} \quad (2)$$

Where:

- i is the province and t is the year.
- $\ln E_{i,t}$ is the natural logarithm of the per capita air pollutants.
- α is the intercept term that represents the region-specific effects that are constant over time.
- $\beta_0, \beta_1, \beta_2, \beta_3$ are the coefficients associated with their respective variables.
- $\ln Y_{i,t}$ is the natural logarithm of the per capita income.
- $X_{i,t}$ is a set of control variables from manufacturing sectors and the population density.
- u_i is the regional effect.
- θ_t is the year effect.
- $e_{i,t}$ is the error term.

Another study by Soonae Park and Youngmi Lee examined the EKC hypothesis for SO_2, CO, and NO_2 across South Korean regions. Their analysis applied fixed, random, and random coefficient models utilizing quadratic and cubic specifications. Results revealed significant regional variations: SO_2 emissions did not consistently follow the EKC pattern across regions, while CO and NO_2 displayed a U-shaped relationship, with NO_2 turning at approximately $27,600[9]. These findings suggest that the EKC's relevance varies significantly depending on the pollutant and region, with energy consumption emerging as a primary factor influencing pollution levels. This study supports the perspective that regional factors and pollutant-specific characteristics play a critical role in EKC outcomes, further challenging the concept of a universal EKC model.

Specification 1

$$\text{Emissions} = f[\text{GRDP}(+), \text{GRDP}^2(-),$$

$$\text{Population}(+), \ln(\text{Cars})(+), \text{Industry}(+), \ln(\text{Energy})(+)]$$

Specification 2

$$\text{Emissions} = f[\text{GRDP}(+), \text{GRDP}^2(-), \text{GRDP}^3(+),$$

$$\text{Population}(+), \ln(\text{Cars})(+), \text{Industry}(+), \ln(\text{Energy})(+)]$$

Where:

- *GRDP* is the gross regional domestic product.
- *Population* is the population density in a region.
- $\ln(Cars)$ is the natural logarithm of the number of cars in the region, representing vehicular emissions.
- *Industry* represents the level of industrial activity, measured by an index of mining and manufacturing products.
- $\ln(Energy)$ is the natural logarithm of total energy consumption (e.g., coal, petroleum, gas).

Jaesung Choi, Robert Hearne, Kihoon Lee, and David Roberts explored the EKC hypothesis in South Korea, focusing on water pollutants, using indicators such as Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). National-level findings indicated an EKC for COD, with a turning point at a GDP per capita of 15–16 million won[10]. However, in river-specific cases such as the Han River, an inverted U-shape was observed for BOD but not for COD, suggesting that localized industrial growth may not yet have reached a stage where economic advancement correlates with environmental improvements. This study concluded that while the EKC hypothesis may hold in certain regions, it does not serve as a reliable predictor across different pollutants or geographical locations.

$$Y = \beta_0 + \beta_1 \cdot \text{pcGDP} + \beta_2 \cdot \text{pcGDP}^2 + \beta_3 \cdot \text{trade} + \beta_4 \cdot \text{population}$$

Where:

- Y represents the level of water pollution at a given time.
- β_i are the coefficients of explanatory variables.
- *pcGDP* is the per capita gross domestic product, serving as a measure of economic development.
- $pcGDP^2$ is the square of per capita GDP.
- *trade* measures the volume or intensity of trade activity, reflecting economic openness and adoption of technology.
- *population* represents the population size which relates to water quality through production of wastewater.

Overall, these studies highlight substantial inconsistencies in the EKC model's applicability. Findings vary widely, especially for sulfur, with some studies supporting an inverted U-shape and others showing no correlation. Such variations indicate that pollutant type and regional factors are crucial. This inconsistency questions the universality of the EKC hypothesis. It suggests that the EKC lacks a unified explanation or logical coherence across pollutants and regions even when observed.

Methods

This study utilizes a longitudinal observational design, focusing on South Korea's 16 metropolitan and provincial regions over 23 years (1999–2021). The research employs panel analysis with random effects to examine the hypothesized inverted U-shaped relationship between economic growth and environmental quality, as described by the Environmental Kuznets Curve (EKC).

The sample comprises 16 administrative regions in South Korea, including Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, Ulsan, Gyeonggi-do, Gangwon-do, Chungcheongbuk-do, Chungcheongnam-do, Jeollabuk-do, Jeollanam-do, Gyeongsangbuk-do, Gyeongsangnam-do, and Jeju-do. These regions represent a mix of highly urbanized and less industrialized areas, providing diverse economic and environmental contexts for the analysis.

Data on Gross Regional Domestic Product (GRDP) per capita, population density, and emissions of four critical pollutants (NOx, CO, PM10, and PM2.5) were collected from the Korean Statistical Information Service[11] and Environment Statistics Portal[12]. The time frame (1999–2021) was selected to capture historical trends and align with the availability of consistent datasets. Panel data was compiled for each region annually.

The study's dependent variables were the levels of air pollutants (NOx, CO, PM10, PM2.5) measured in micrograms per cubic meter. The independent variables included GRDP per capita, measured in South Korean Won, and GRDP per capita squared to test for the inverted U-shape. Control variables comprised population density (residents per square kilometer), regional effects, and year effects. Environmental data was obtained through air quality monitoring networks, while GRDP figures were sourced from statistical bureaus.

Each region's historical economic and environmental data were gathered and consolidated into a panel dataset for data compilation. A random effects model incorporating GDP, GDP squared, and control variables was developed to test the Environmental Kuznets Curve (EKC) hypothesis. The preliminary analysis used descriptive statistics and correlation analysis to assess data trends and relationships. Finally, a panel analysis with random effects was conducted in the regression analysis to estimate the relationship between GDP and pollutant levels, focusing on the coefficients of GDP and GDP squared.

The panel analysis of random effects was applied to account for unobserved heterogeneity across regions and periods. The regression model used GDP per capita and GDP squared to test for the EKC's characteristic inverted U-shaped relationship. Statistical software (e.g., STATA or R) was employed to compute the coefficients, significance levels, and goodness-of-fit measures.

The researchers' model analyzes explicitly four pollutants—NOx, CO, PM10, and PM2.5—against GDP per capita and GDP per capita squared to detect the characteristic inverted U-shape of the EKC. Closely mirroring the model from Kim et al., the regression equation for the model was structured as follows, using natural logarithm to mitigate the issue of heteroskedasticity[13]:

$$\ln(P_{t,r}) = \beta_0 + \beta_1 \ln(\mathrm{GDP}_{t,r}) + \beta_2 \ln(\mathrm{GDP}_{t,r})^2 + \beta_3 D_{t,r} + \mathrm{RE}_t + Y_r + \varepsilon$$

Where:

- t represents the years from 1999 to 2021, and r denotes the region from 1 to 16.
- P is the level of each pollutant.
- β_1 are the coefficients of explanatory variables.
- *GDP* is the GDP per capita.
- D represents population density.
- *RE* is the regional effect.
- Y is the year effect.
- ε is the error term.

The use of a simple quadratic function (GRDP and GRDP2) to model pollutant trends assumes that the relationship between economic growth and pollution strictly follows an inverted U-shape. This assumption would ignore the possibility of more complex dynamics, such as cubic or logistic relationships. However, the current study aimed to check the original EKC hypothesis and not to find a more accurate yet complex model, so the use of a quadratic function was deemed appropriate in order to remain consistent with the original EKC framework. A random effects model was used to estimate the parameters.

The study adhered to ethical guidelines by using publicly available aggregated data, ensuring no breach of confidentiality or privacy. Data sources were transparently cited, and no interventions involving human participants required informed consent. The research complies with environmental and statistical ethics to ensure accuracy and integrity in reporting results.

Results

The findings reveal an inverse U-shape for NOx, CO, and PM2.5. This is because, for these three pollutants, the real GDP per capita income squared value was all negative. A negative value for the real GDP squared correlates to an inverted U-shape because the model is a quadratic function. Suppose the coefficient of the squared term is negative in a quadratic function. In that case, that means it is concave down and will be an upside-down parabola. Therefore, those three pollutants will have an inverted U-shape, while the PM10 will keep increasing - a monotonic curve. This inconsistency across pollutants indicates that environmental and economic dynamics may vary based on the pollutant's nature and regional regulations.

Moreover, it can be noticed that population density does not have a significant relationship with CO and NOx; however, it negatively correlates with PM10 and PM2.5. This is counterintuitive to the understanding of pollutants. We came to this conclusion because the coefficient of population density is very small compared to the others. Scaling would be needed if we were to compare coefficients across different pollutants, but within a single model, the noticeably smaller coefficient of population density compared to GDP and GDP squared is sufficient to conclude it has less significance. In a general sense, population density and pollutants have a positive relationship. In a study conducted by Shuaishuai Han and Bindong Sun, they concluded that a higher population density "will generate more emissions." Moreover, they added that "population density is positively associated with PM2.5 concentrations."[14] This suggests that unobserved regional factors could have affected the results, or the data was not enough to reveal the expected positive relationship. If regional factors were the cause, then it would align with the findings from the literature review, which indicate that local factors and specific pollutant characteristics influence the EKC's applicability across different contexts.

One possible explanation could come from a historical and geographical analysis specific to South Korea. For example, according to a report released by the Korea Environment Institute in 2016[15], Wonju, a small city in a rural area, has a higher PM2.5 concentration than Seoul, the capital of the country with the highest population density, as a result of the combination of westerlies carrying particulate matters from China and the Taebaek mountains in the east of the city blocking the airflow. Also noteworthy is that the rapid industrialization in South Korea since the 1970s was strongly government-led, strategically focusing on certain regions previously underdeveloped. As a result, there are multiple industrial complexes outside of the more densely populated Greater Seoul area, such as Pohang, where POSCO, the first and the biggest steel mill in the country, is located. Both Wonju and Pohang have a population density of around 400/km2, which is 5 times less than that of Seoul. Yet, our data shows that they had significantly higher particulate matter concentration than Seoul. Considering that the Taebaek mountains span about 500km, which is nearly half of the length of South Korea, and that the economic planning in the 1970s had a great emphasis on the heavy and chemical industry[16], these two are merely examples representing a general pattern.

Furthermore, the turning points for NOx, CO, and PM2.5 are 19502, 7403, and 950131, respectively. Nairui Liu and Lidia Morawska noted that these turning points are not universal. These researchers determined that the EKC is "highly country-specific" and "extremely difficult to predict" the position of the turning point "based on the historical development."[17] The extraordinarily high turning point for PM2.5 highlights the implausibility of the quadratic model suggested by the original EKC hypothesis and the need for a model of a higher degree to accommodate more complex shapes such as the (inverted) N-shape of a cubic model.

This idea is further emphasized by the figures found in Table 1 below and those from the existing literature.

The turning points from Kim et al. and Park and Lee are different from the ones found in our analysis and differ from each other. For example, Kim et al. suggest 7,440 thousand KRW as a turning point for CO, while Park and Lee indicate between 26,400 and 30,000 USD (approximately 38,000 and 43,000 thousand KRW). This exemplifies the existing discrepancy when calculating the turning points, even for a single country. Park and Lee also noted that CO has a one-dominant U-shaped curve, contrasting with the inverted U-shape result.

In addition, the reported R-squared values (e.g., 0.203 overall for NOx) indicate that the model explains only a small fraction of the variation in pollutant levels. This suggests that the model may be missing critical explanatory variables. However, the reported R-squared is not small compared to other existing literature. For example, the highest R-value among the models in Kim et al. was only 0.2338. Rather than indicating a deficiency unique to our model, this finding highlights the broader implausibility—or at least weak convincingness—of the EKC hypothesis itself, given the limited explanatory power observed in multiple studies.

Also, the general difference between oxide compounds (CO, NOx) and particulate matter (PM2.5, PM10). In contrast to the inverted U-shape of oxide compounds, the curves for particulate matter were either monotone, in the case of PM10, or nearly monotone, with a practically unreachable high turning point, in the case of PM2.5. As none of the previous works on EKC in South Korea dealt with particulate matters, this phenomenon requires further attention.

Overall, we don't agree that there is significant evidence that the mentioned pollutants exhibit an inverted U-shape. Park and Lee, for example, reported a (non-inverted) U-shape for both CO and NO2. Our understanding from the literature review is that there is no consensus on which pollutant exhibits an inverted U-shape and which does not, which is the reason for the skepticism

Variable	NOx	CO	PM10	PM2.5
(Ln) Real GDP Per Capita Income	1.1743	2.2483	0.6353	2.5409
(Ln) Real GDP Per Capita Income Squared	-0.0659	-0.1138	0.0057	-0.0923
Population Density	-9.253e-05	2.77e-06	-0.0002	-0.0002
Constant	5.3442	-1.1919	0.4309	-9.3174
Number of Observations	368	368	368	368
Number of Metropolitan Areas/Provinces	16	16	16	16
Within R-Squared	0.2635	0.1651	0.2455	0.0585
Between R-Squared	0.1967	-0.0034	0.2876	0.4839
Overall R-Squared	0.2030	0.0548	0.2743	0.4356
Turning Point	19502	7403	-	950131

Table 1 Regression Results for Testing the Environmental Kuznets Curve Hypothesis in South Korea
Note: Units for turning point and GDP per capita are in 1000 won, and units for emissions are in kilograms.

about the EKC hypothesis. We interpret the extraordinarily high turning point for PM2.5 and the low turning point for CO as indicating the limit of the quadratic model suggested by the basic EKC model, suggesting that the relationship can better be expressed with a higher-degree equation, a cubic N-shape, for example.

Discussions

This study highlights that the Environmental Kuznets Curve (EKC) demonstrates a conceptual link between economic growth and environmental quality, suggesting an inverted U-shaped relationship. However, findings indicate that this model has limitations in capturing the complex relationship between economic activities and environmental degradation. Specific cases, such as those in Houston, Texas, reveal the inadequacies of the EKC in addressing industrial specialization and population density as significant factors influencing pollution. The study also emphasizes the importance of long-term data and specialized models in refining the EKC's applicability.

The implications of these findings underscore the need for multi-variable models to enhance the EKC's accuracy. For example, integrating variables such as industrial activity, energy consumption, and urbanization can provide deeper insights into the relationship between economic growth and pollution levels. The case of Houston, with its economic prosperity but poor air quality due to petrochemical industries, highlights how industrial specialization influences environmental outcomes. These findings contribute to the broader understanding of environmental economics, filling gaps in how economic prosperity interacts with sustainability goals. Furthermore, longitudinal analyses, such as comparing the industrialization paths of China and South Korea, could reveal the long-term effects of policy interventions and economic strategies.

The research objectives were to assess the accuracy and applicability of the EKC model in predicting environmental outcomes. The study met these objectives by identifying critical factors omitted in traditional EKC models. It also highlighted unexpected outcomes, such as the significant impact of urban population density on particulate matter pollution. These findings reveal that the EKC's traditional framework oversimplifies the intricate dynamics of environmental degradation, emphasizing the necessity of specialized, context-sensitive approaches.

Future research should focus on developing EKC models incorporating additional variables, such as industrial activity levels, energy consumption, and urbanization trends. Expanding the dataset to include earlier historical periods (e.g., from 1950 onwards) could provide more comprehensive insights into long-term trends and the impact of significant policy interventions like the Clean Air Act of 1970. Moreover, specialized models analyzing the relationship between population density and particulate matter (e.g., PM 2.5 and PM 10) should be explored to inform urban planning and pollution control strategies. Similarly, the scope of pollutants is broadened beyond the four analyzed in this study. In our research, we only focused on NOx, CO, PM10, and PM2.5. Although these pollutants do not represent the full spectrum of environmental pollutants, we tried to limit the type of air pollutants to the ones often studied in the literature so that we can directly compare the results. Including greenhouse gases (e.g., CO_2, CH_4) or water pollutants in further research could yield a more holistic understanding of environmental degradation. Tailored interventions, such as enhancing public transportation, increasing urban green spaces, and enforcing stricter emissions standards, are recommended to mitigate health risks and improve air quality.

This study acknowledges several limitations, including its reliance on secondary data sources and the limited number of variables examined in the existing EKC framework. The exclusion of factors like industrial specialization, regional policy differences, and socioeconomic variables may have impacted the generalizability of the findings. Additionally, the relatively short analysis timeframe limits the ability to evaluate long-term trends and the effectiveness of policy measures. These constraints highlight the need for further studies employing more comprehensive datasets and methodologies.

Refining the EKC framework to include additional variables, extended datasets, and specialized models offers a pathway toward more accurate and actionable insights into the interplay between economic growth and environmental sustainability. By moving beyond the traditional inverted U-shaped curve and adopting a context-sensitive approach, researchers and policymakers can develop strategies that balance economic prosperity with ecological preservation, ensuring sustainable development for future generations.

Conclusion

The Environmental Kuznets Curve (EKC) serves as a conceptual framework linking economic growth to environmental quality. By positing that pollution levels initially increase with rising income but eventually decline as nations reach higher levels of development, the EKC underscores the potential for achieving both economic prosperity and environmental sustainability. With the implementation of appropriate regulatory measures and technological advancements, high-income nations can mitigate environmental degradation.

However, our findings reveal that the EKC is not universally applicable to all pollutants or contexts. Studies conducted in Houston and South Korea reveal inconsistencies in the EKC's predictive capabilities, with industrial activities and the characteristics of specific pollutants playing a significant role. These findings suggest that the EKC model requires refinement, incorporating additional variables to better represent complex environmental-economic relationships beyond a simple inverted U-shaped curve.

Moreover, regional efforts, such as stricter regulations and localized pollution controls, have the potential to significantly enhance environmental quality. Researchers emphasize the importance of tailoring pollution-specific strategies that align with local conditions and urge policymakers to integrate these insights into their frameworks.

Despite its limitations, the EKC remains a valuable tool—not as a universal model but as a flexible framework that can be adapted to support sustainable development through nuanced, context-sensitive approaches.

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