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ASSESSING ENVIRONMENTAL SUSTAINABILITY AT THE REGIONAL AND DEVELOPMENT LEVEL

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Abstract: The study examines the relationship between environmental sustainability and economic growth across countries and income levels by testing the Environmental Kuznets Curve hypothesis using panel data methods. In the analysis, CO_2, agricultural CH_4 and agricultural N_20 emissions are used as dependent variables and three models are constructed based on various economic and agricultural indicators. The dataset covers broad country groups such as the Arab World, Euro Area, European Union, OECD, IBRD, and East Asia-Pacific, as well as low, middle and high income economies. Unit root tests show that most variables are stationary at level. Findings related to CO_2 emissions reveal that the classical inverted U shaped Environmental Kuznets Curve does not hold for any country group, instead U, N and inverted N shaped relationships emerge. By income level, low-income countries exhibit an N type curve, middle income countries an inverted N structure, and high income countries a U shaped pattern. This indicates that environmental pressures do not consistently decline with rising income but fluctuate depending on economic structure, energy policies and technical capacity. For agricultural CH4 emissions, only the European Union and Euro Area support the classical inverted U form, while U, N, and inverted N shaped structures appear in other regions. By income group, low income countries exhibit a U shaped curve, middle income countries an inverted N curve, and high income countries an inverted U structure. For agricultural N_2O emissions, the dominant curve type is N shaped across both country groups and income levels. Overall, the results demonstrate that environmental sustainability is determined less by income growth and more by structural transformation, environmental regulation, technological development, and sectoral characteristics. These findings highlight the necessity of country and income specific policy strategies instead of uniform global environmental policies.

Keywords: Panel data analysis, Environmental Kuznets curve, Economic growth, Environmental sustainability, CO_2 emissions

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1. Introduction

Today, environmental problems have evolved into multidimensional crises that directly affect not only natural habitats but also social welfare, economic growth, and the living rights of future generations. In particular, global farming and climate change have ceased to be issues confined to environmental sciences and have instead become structural problems that influence numerous domains ranging from economics and politics to public health and international relations. The rapid increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases due to human activities disrupts the balance of climate systems, leading to rising global temperatures, droughts, desertification, extreme weather events, sea level rise, and agricultural yield losses (Meehl et al., 2007; IPCC, 2017). In this context, the relationship between humans and nature requires renewed reflection and critical reassessment.

Human activities impact nature in ways that extend far beyond carbon emissions. Agriculture, industry, energy consumption, urbanization, and deforestration all directly contribute to the deterioration of environmental balance. While Norby and Lou (2004) emphasize that human driven influences play a decisive role in the carbon cycle and energy flows of ecosystems, Davidson and Janssens (2006) demonstrate that these impacts threaten climate systems and ecological processes on a global scale. Considering the interconnectedness of living and non-living components in nature, the destruction of a single organism or habitat can trigger a domino effect across the entire ecosystem. Such disruptions may ultimately lead to consequences as severe as damage to food chains and destabilization of natural ecological equilibrium (Sarı, 2016).

The tension between economic development and environmental sustainability represents one of the most challenging dilemmas of the modernization process. In developing countries, inadequate infrastructure, rapid population growth and pressures from urbanization often push environmental concerns into the background, jeopardizing long term sustainable development goals (Türküm, 1998; Özerkmen, 2002). In the case of Türkiye, repeated exceedances of air pollution thresholds in several cities after 2010, rising water pollution levels,

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and the conversion of agricultural lands into urban areas clearly indicate that environmental pressure has surpassed the carrying capacity of natural systems.

Addressing environmental issues solely from a biophysical perspective has become insufficient, an economic perspective is now equally essential. At this point, the field of ecological economics offers a comprehensive framework by analyzing the reciprocal relationship between the economy and the environment, enabling an integrated assessment of both the sustainability of resource use and the environmental impacts of economic activities (Costanza et al., 1991). The sustainable development approach, which gained international recognition particularly in the 1990s, is based on the notion that economic growth should ocur within ecological limits. This approach prioritizes development models that safeguard not only current needs but also the rights and resource access of future generations. The rapid increase in energy consumption and greenhouse gas emissions driven by industrialization and population growth places significant pressure on environmental carrying capacity, thereby highlighting the need for nature compatible, long term development strategies. In this context, ecological economics emerges not only as an environmentally sensitive economic model but also as one of the fundamental pillars of sustainable development.

In this study, the relationship between, income, and greenhouse gas emissions is examined through various dimensions. This relationship is primarily grounded in the framework of the Environmental Kuznets Curve (EKC). Kuznets (1955) posited that income distribution initially deteriorates with economic growth and development, but that income inequality subsequently decreases as income continues to rise. Referenced in economic literature as the Environmental Kuznets Curve, this hypothesis was adapted in the 1990s to explain the relationship between economic growth and environmental pollution/degradation (Başar and Temurlenk, 2007).

Studies employing the EKC generally converge on a common consensus. Fundamentally, economic income growth accompanied by population growth triggers an increase in consumption; to meet this demand, the increased energy usage by industrial units results in carbon dioxide emissions. However, this phenomenon does not create a vicious cycle; as the developing economy advances technologically and in terms of environmental awareness, pollution-reducing measures are implemented after a certain turning point, establishing a negative correlation between income growth and environmental pollution.

Certain studies indicate that population growth and the increase in per capita energy consumption do not necessarily follow parallel trajectories (Cohen, 1997). For instance, among developed nations, per capita commercial energy consumption declined by 4% in the United States and by 17% in Denmark during the 1971–1991 period (World Resources Institute, 1994). Conversely, it was determined that energy usage in the United States increased by 38% due to population growth during the 1940–1969 period. On the other hand, studies conducted on Turkey, considered a developing country, indicate that energy demand was 98 Mtoe (Million Tonnes of Oil Equivalent) in 2001 and projected it to reach 308 Mtoe by 2020 (Oğulata and Oğulata, 2002).

When comparing per capita energy consumption with per capita Gross National Product (GNP) in terms of Purchasing Power Parity (PPP), it is observed that energy consumption increases in correlation with income growth in high-income countries. This suggests that the EKC assumes an inverted "U" shape primarily in developed nations. Regarding the emergence of Kuznets curves, the primary objective of this study was to determine the level of environmental awareness between 1990 and 2016 and to forecast future levels of the emissions in question. The secondary objective can be summarized as the analytical evaluation of the factors affecting greenhouse gas emissions across different income and country groups, specifically regarding their relationship with environmental pollution contingent on income and population density within the selected timeframe.

Using a panel regression model, the study derived EKC based on country groups and global income groups, and evaluated the results. An attempt was made to determine the trajectory of CO_2, N_2O, and CH_4 emissions in parallel with income growth. While existing literature includes similar studies (Stern et al., 2004; Başar et al., 2007; Akyıldız, 2009; Güvenek and Alptekin, 2010; Tokatlıoğlu and Atan, 2009; Tutulmaz et al., 2012; Franklin and Ruth, 2012; Ruamsuke et al., 2015; Valverde et al., 2015; Abbasi et al., 2023; Narcisse et al., 2023), this study can be considered more comprehensive, particularly regarding the specific country groups examined and the panel data analysis employed. Furthermore, while this study enables the evaluation of differences in per capita energy consumption and carbon emissions between developed and developing countries through the lens of sustainable economic development, it also yields significant findings for the formulation of effective environmental policies.

2. Materials and Methods

2.1. The Data

The primary material of this study, which investigates the relationship between income levels, and greenhouse gas emissions, consists of statistical datasets obtained from national and international institutions. The analytical structure is examined at two levels, country groups and income groups. For each country group, separate panel regressions are estimated to evaluate the Environmental Kuznets Curve. All data were obtained from the “World Development Indicators” database published by the World Bank. The time period examined

in this study is 1990–2016 (Table 1). In this study, each data set was constructed separately based on country groups and income groups. Within this scope, the Arab World (22 countries), the Euro Area (19 countries), East Asia (38 countries), Pacific Countries (58 countries), The Euro and Central Asia group, the European Union (28 countries), the 189 countries within the International Bank for Reconstruction and Development (IBRD), 20 countries within the Organization for Economic Cooperation and Development (OPEC), and the 194 countries globally were taken into consideration. Additionally, 20 countries in the low income group, 96 in the middle income group, and 78 in the high income group were included.

Table 1. Data and variable definition

Variables	Explanation	Reference
GDP	GDP per capita, PPP (current international $)	Worldbank (WDI)
CO_2	Carbon dioxide emission (mg/m^3)	Worldbank (WDI)
N_2O	Agricultural Nitrous oxide emission (mg/m^3)	Worldbank (WDI)
CH_4	Agricultural methane emission (mg/m^3)	Worldbank (WDI)
AGDP	Agriculture, forestry, and fishing, value added (% of GDP)	Worldbank (WDI)

2.2. Empirical Model

In this study, to specifically capture the structural relationship between economic development and environmental degradation, a reduced-form Environmental Kuznets Curve (EKC) model is adopted. Following the standard EKC literature (Grossman and Krueger, 1995; Stern, 2004), the model focuses on the direct impact of income levels on emissions.

The panel data model in which total CO_2 emissions are used as the dependent variable (equation 1):

$$CO_{2\ it} = \beta_{0it} + \beta_1 GDP_{it} + \beta_{2it} GDP_{it}^2 + \beta_{3it} GDP_{it}^3 + \varepsilon_{it} \quad (1)$$

In the model presented in Equation (1), where CO_2 emissions serve as the dependent variable, the emissions of country *i* at time *t* are considered. For the income variable (GDP), per capita income for country *i* at time *t* is used as the independent variable. To capture the EKC, the squared and cubic forms of income are included in the model to reflect nonlinear effects of income growth.

In Equation (2) and (3), models are constructed to obtain the agricultural EKC for emissions originating from the agricultural sector. The dependent variable agricultural N_2O (ANO) in equation (2) represents agricultural N_2O emissions of country *i* at time *t*, whereas the dependent variable agricultural CH_4 (ACH_4) in equation (3) represents agricultural CH_4 emissions of country *i* at time *t*, the income variable refers to agricultural value-added (AGDP) for each country *i* at time *t*. In all three equations, β_0 denotes the constant term and Ɛ represents the error term.

The panel models in which AN_2O ve ACH_4 emissions are used as the dependent variables:

$$AN_2O_{it} = \beta_{0it} + \beta_1 AGDP_{it} + \beta_2 AGDP_{it}^2 + \beta_3 AGDP_{it}^3 + \varepsilon_{it} \quad (2)$$

$$ACH_{4\ it} = \beta_{0it} + \beta_1 AGDP_{it} + \beta_2 AGDP_{it}^2 + \beta_3 AGDP_{it}^3 + \varepsilon_{it} \quad (3)$$

In all three models, it is assumed that as income (GDP) increases, energy demand rises accordingly, therefore, CO_2 , AN_2O and ACH_4 emissions are expected to increase.

Considering the parameters estimated in the model, an EKC is derived for each country group to examine the relationship between environmental pollution and income. Based on these results, the following hypotheses are evaluated.

$If\ \ \beta_1 = \beta_2 = \beta_3 = 0$, there is no relationship between income and environmental pollution.

$If\ \ \beta_1 > 0\ \beta_2 = \beta_3 = 0$, environmental pollution increases as income increases.

$If\ \ \beta_1 > 0\ \beta_2 < 0\ and\ \beta_3 = 0$, there is an inverted U shaped relationship between income and environmental pollution.

$If\ \beta_1 < 0\ \beta_2 > 0\ and\ \beta_3 = 0$, there is a U shaped relationship between income and environmental pollution.

$If\ \beta_1 > 0\ \beta_2 < 0\ and\ \beta_3 > 0$, there is an N shaped relationship between income and environmental pollution.

$If\ \beta_1 < 0\ \beta_2 > 0\ and\ \beta_3 < 0$, there is an inverted N shaped relationship between income and environmental pollution (Akyıldız, 2009).

3. Results

When conducting panel unit root tests. It is essential that each variable be included in the regression analysis at its stationary level in order to avoid spurious regression problems. Therefore, testing the stationarity of the variables is of critical importance. The *Im, Peseran, Shin (IPS)* unit root test results used to examine the stationary of each series are presented in Table 2.

In the analyses, two specifications were employed: a constant only model (C) and a constant plus trend model (C/T). According to the results, the null hypothesis (H_0) is rejected for CO_2, agricultural CH_4, agricultural N_2O, GDP, GDP^2,GDP^3 AGDP. $AGDP^2$ and $AGDP^3$ in both models (with the exception of GDP^2 in the constant only model), indicating that these series are stationary level, i.e.,I(0). On the other hand, the first differences of the variables G and N are found to be stationary, meaning they are I(1) in both model specifications. Lag lengths for all variables, were determined automatically based on the Schwartz

Information Criterion (SIC) Overall, the results of the Im, Pesaran, Shin (IPS) and Levin, Lin, Chu (LLC) unit root tests indicate that all variables included in the analysis are stationary at level I(0), except for the GDP variable. The AGDP variable becomes stationary after first differencing.

Table 2. IPS and LLC unit root test results

Unit root tests		IPS		LLC	
Variables	Model	W statistics	Result	t-statistics	Result
CO_2	C	-1.210*	I(0)	-5.157*	I(0)
	C/T	-4.998*	I(0)	-6.634*	I(0)
ACH_4	C	-1.889**	I(0)	-1.942**	I(0)
	C/T	-1.926**	I(0)	-7.019*	I(0)
AN_2O	C	-21.651*	I(I)	-31.505*	I(1)
	C/T	-22.326*	I(I)	-13.834*	I(1)
GDP	C	-23.520*	I(I)	7.956	-
	C/T	-22.688*	I(I)	-9.532*	I(0)
GDP^2	C	5.416	-	11.735	-
	C/T	-2.376*	I(0)	-20.858*	I(0)
GDP^3	C	-17.613*	I(0)	2.105	-
	C/T	-20.859*	I(0)	-3.247*	I(0)
AGDP	C	-16.086*	I(I)	7.956	-
	C/T	-13.911*	I(I)	-9.532*	I(0)
$AGDP^2$	C	-17.613*	I(0)	11.735	-
	C/T	-20.859*	I(0)	-20.858*	I(0)
$AGDP^3$	C	-16.086*	I(I)	2.105	-
	C/T	-13.911*	I(I)	-3.247*	I(0)

* and ** indicate significance at 1 % and 5 % levels, respectively.

Table 3. Panel data estimates and results based on CO_2 (by country groups)

Country Group	Panel Model	β_1	β_2	β_3	Prob.	R^2	Adj. R^2	Kuznets Curve Model
Arab World	Balanced	< 0	> 0	$= 0$	0.0000	0.83	0.81	U
Euro Area	Cross Section Weighted	< 0	> 0	$= 0$	0.0002	0.76	0.77	U
Europe and Central Asia	Balanced	> 0	< 0	> 0	0.0001	0.67	0.67	N
European Union	Balanced	< 0	> 0	$= 0$	0.0003	0.71	0.70	U
IBRD	Period Weighted	< 0	> 0	< 0	0.0000	0.68	0.66	И
OECD	Balanced	< 0	> 0	< 0	0.0000	0.72	0.74	И
East Asia and Pacific	Period Weighted	> 0	< 0	> 0	0.0000	0.66	0.68	N
World	Balanced	< 0	> 0	< 0	0.0000	0.72	0.74	И

3.1. Kuznets Curve Approach Based on CO_2

The fixed effects panel data analysis conducted using CO_2 emissions reveals various forms of the relationship between economic growth and environmental pollution across different country groups. The panel data model aims to determine the specific form of the EKC by examining the signs of the coefficients β_1, β_2 and β_3.

The results presented in Table 3 show that none of the eight country groups examined exhibit the classical inverted U shaped EKC. Instead, U shaped, N shaped, and inverted N (∩) curve structures are observed. In the Arab World, Euro Area, and European Union groups, the coefficients $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 = 0$ indicate a positive U shaped relationship. This model suggests that environmental pollution decreases during the early stages of economic growth but does not continue to decline after a certain threshold, implying that no structural environmental improvement takes place.

In contrast, an N shaped EKC is observed for the Europe and Central Asia group as well as the East Asia and Pacific group. The curve indicates that environmental degradation first increases with rising income, then decreases, but subsequently begins to rise again at higher income levels. This finding suggests that the environmental impacts of economic development are not stable and that insufficient political, technological, or sectoral transformation may cause renewed environmental pressure at advanced stages of income growth.

One of the most noteworthy findings is the inverted N (∩) curve observed for OECD countries. IBRD countries, and the world as a whole. According to this pattern,

environmental degradation initially decreases as income rises. However, at higher income levels, pollution begins to increase again. This suggests that environmental gains may not be sustainable in the long term and that environmental pressures can re-emerge as consumption patterns intensify and production scales expand.

It is evident that the panel data estimates used in all models are statistically significant. All probability values fall below the 1% threshold, indicating a high level of reliability. Moreover, the R^2 and adjusted R^2 values exceed 70% for most country groups, demonstrating strong explanatory power of the models. In particular, the models exhibit robust structures for the Arab World (81%), the OECD (74%), and the world as a whole (71%).

In conclusion, the analysis shows that the classical inverted U shaped Kuznets Curve is not observed for any country group. Instead, U shaped, N shaped, and inverted N patterns emerge. This indicates that environmental sustainability cannot be achieved solely through income growth, rather, policymakers must support economic development with environmental awareness, technological innovation, and structural reforms. The fact that each country group exhibits different curve structures underscores the need for flexible approaches tailored to regional and structural differences, rather than uniform solutions to environmental problems. These findings demonstrate that environmental sustainability cannot be secured through economic growth alone, structural transformation, investment in technology, diversification of energy sources, and effective implementation of environmental policies are critical. The presence of distinct curve forms across country groups further highlights that country specific strategies are necessary instead of a one size fits all policy approach.

Table 4 presents the fixed effects panel data analysis results for countries classified by income level based on CO_2 emissions. This analysis evaluates the relationship between economic growth and environmental pollution (CO_2 emissions) for low, middle and high income countries within the framework of the Kuznets Curve. The findings indicate that different Kuznets Curve patterns emerge for each income group.

For low income countries, the estimated coefficients ($\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$) indicate an "N shaped" Kuznets Curve. In this case, environmental pollution initially increases with rising income, then decreases, but begins to increase again at higher income levels. This curve pattern suggests that environmental pressures in these countries cannot be fully controlled through income growth alone, largely due to limited environmental awareness and inadequate infrastructure. In other words, the technological capacity, administrative capability, and environmental regulations required to translate economic growth into environmental improvement have not yet been effectively implemented.

For middle income countries, the coefficient structure ($\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 > 0$) indicates an inverted N shaped Kuznets Curve. This model shows that economic growth initially reduces environmental degradation, but at more advanced income levels, pollution begins to rise again. This suggests that in middle income countries, development has a positive environmental effect only up to a certain point, however, this improvement is not sustainable, and pollution eventually increases once more due to rising energy demand, expanding production volume and accelerating urbanization.

For high income countries, the coefficient structure ($\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 = 0$) indicates a U shaped curve. This pattern shows that environmental degradation decreases as income rises, and that this improvement persists beyond a certain income level. In these countries, advanced environmental policies, technological innovations, and sustainable production processes enable economic growth to progress alongside environmental improvement. The shift of both the public and private sectors toward environmentally friendly investments is one of the key factors supporting this curve pattern.

Across all income groups, the statistical validity of the model is high. The probability values are significant ($p < 0.01$). The R^2 and adjusted R^2 values are found to be 70% for low income countries. 76% for middle income countries, and 82% for high income countries. These ratios indicate that the models explain the dataset well and that the results obtained are reliable.

Overall, the analyses indicate that income level differentiates environmental impacts, that each country group experiences the environmental transition process in distinct ways, and that stratified strategies based on income level are required rather than a one size fits all environmental policy. For low income countries, strengthening environmental infrastructure should be prioritized, for middle income countries, sustainable technologies and urbanization policies are essential and for high income countries, innovative solutions aimed at preserving existing environmental gains should take precedence.

3.2. Kuznets Curve Approach Based on Agricultural CH_4

According to the panel data analysis results presented in Table 5, the relationship between agricultural methane (CH_4) emissions and economic growth various across country groups. The findings for the Euro Area and the European Union support the Environmental Kuznets Curve hypothesis. In both groups, a classical inverted U shaped relationship is observed, indicating that methane emissions initially increase with rising income and subsequently decrease after reaching a certain income level. This pattern suggests that while economic growth in its early stages contributes to environmental degradation, emissions begin to decline once environmental awareness increases and clean technologies are adopted.

On the other hand, in the Arab World, a U shaped relationship is identified, indicating that emissions decrease as income rises but increase again at higher

income levels. This pattern moves in the opposite direction of the inverted U hypothesis and therefore does not support the EKC model. Similarly, for Europe and Central Asia, the IBRD group, the OECD, and the world as a whole, the estimates reveal an inverted N (∩) shaped relationship. In these models, emissions decrease with rising income but begin to increase again, suggesting that environmental pressure follows a cyclical pattern depending on income levels. This outcome indicates that structural changes, industrial intensity, and policy differences play a significant role in shaping environmental dynamics in these country groups.

For East Asia and Pacific counties, an N shaped curve is defined. In this case, methane emissions initially increase with economic growth, then decrease, and subsequently rise again. Such a pattern suggests that in rapidly industrializing countries, environmental pressure may increase periodically, independent of income levels. In conclusion, while the Environmental Kuznets Curve hypothesis is validated only for the European Union and Euro Area, the presence of different curve types in other regions indicates that environmental impacts vary significantly depending on countries' development levels, production structures and environmental policies.

Table 4. Panel data estimates and results based on CO_2 (by income groups)

Income Group	Panel Model	β_1	β_2	β_3	Probability	R^2	Adj. R^2	Kuznets Curve Model
Low	Cross Section Weighted	> 0	< 0	> 0	0.0000	0.69	0.70	N
Middle	Balanced	< 0	> 0	< 0	0.0000	0.79	0.76	И
High	Balanced	< 0	> 0	$= 0$	0.0000	0.82	0.82	U

Table 5. Panel data estimates and results based on CH_4 (by country groups)

Country Group	Panel Model	β_1	β_2	β_3	Prob.	R^2	Adj. R^2	Kuznets Curve Model
Arab World	Cross Section Weighted	< 0	> 0	$= 0$	0.0002	0.76	0.77	U
Euro Area	Balanced	> 0	< 0	=0	0.0000	0.83	0.86	Ո
Europe and Central Asia	Balanced	< 0	> 0	< 0	0.0000	0.66	0.65	И
European Union	Period Weighted	> 0	< 0	=0	0.0000	0.86	0.86	Ո
IBRD	Balanced	< 0	> 0	< 0	0.0000	0.61	0.60	И
OECD	Balanced	< 0	> 0	< 0	0.0000	0.86	0.85	И
East Asia and Pacific	Cross Section Weighted	> 0	< 0	> 0	0.0000	0.73	0.71	N
World	Period Weighted	< 0	> 0	< 0	0.0000	0.66	0.65	И

According to the analysis results presented in Table 6, the relationship between agricultural (CH_4) emissions and economic growth varies across income groups. For low income countries, the estimated coefficients ($\beta_1 < 0$ and $\beta_2 > 0$) indicate a U shaped Environmental Kuznets Curve. This suggests that methane emissions initially decrease as economic growth begins, but after reaching a certain level of income, emissions start to rise again. Such a pattern demonstrates that environmental improvements are not sustainable and that environmental pressure increases once more in the later stages of economic growth.

For middle income countries, the coefficient structure ($\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$) results in an inverted N (∩) shaped curve. This pattern indicates that emissions initially increase with economic growth, then decline, but eventually Show an upward trend again. This suggests that environmental protection efforts are only temporarily effective as income rises, and that the economic structure ultimately generates renewed environmental pressure over time.

For high income countries, the coefficient structure ($\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 \approx 0$) corresponds to the classical inverted U shaped Environmental Kuznets Curve. This model indicates that economic growth initially leads to environmental degradation in high income countries, but after a certain income threshold, environmental impacts begin to decline. In other words, methane emissions can be brought under control in developed countries through environmental awareness, technological advancement, and effective policy implementation.

In conclusion, the environmental impacts of economic growth manifest differently across income levels, and a positive turning point toward environmental sustainability is observed only in high income countries. This demonstrates that environmental policies and technological transformation yield more pronounced and effective results in developed economies.

Table 6. Panel data estimates and results based on agricultural CH_4 (by income groups)

Income Group	Panel Model	β_1	β_2	β_3	Probability	R^2	Adjusted R^2	Kuznets Curve Model
Low	Cross Section Weighted	< 0	> 0	$= 0$	0.0001	0.78	0.79	U
Middle	Balanced	< 0	> 0	< 0	0.0000	0.75	0.76	И
High	Balanced	> 0	< 0	=0	0.0003	0.88	0.88	Ո

Table 7. Panel data estimates and results based on agricultural N_2O (by country groups)

Country Group	Panel Model	β_1	β_2	β_3	Probability	R^2	Adjusted R^2	Kuznets Curve Model
Arab World	Balanced	< 0	> 0	< 0	0.0000	0.86	0.85	И
Euro Area	Balanced	< 0	> 0	< 0	0.0000	0.86	0.85	И
Europe and Central Asia	Cross Sectional Weighted	< 0	> 0	$= 0$	0.0001	0.76	0.76	U
European Union	Balanced	< 0	> 0	< 0	0.0003	0.71	0.70	Ո
IBRD	Period Weighted	> 0	< 0	=0	0.0000	0.81	0.83	Ո
OECD	Balanced	< 0	> 0	< 0	0.0000	0.89	0.87	И
East Asia and Pacific	Balanced	> 0	< 0	=0	0.0000	0.86	0.86	Ո
World	Balanced	< 0	> 0	< 0	0.0000	0.81	0.83	Ո

Table 8. Panel data estimates and results based on agricultural N_2O (by income groups)

Income Group	Panel Model	β_1	β_2	β_3	Probability	R^2	Adjusted R^2	Kuznets Curve Model
Low	Cross Section Weighted	> 0	< 0	> 0	0.0001	0.63	0.65	N
Middle	Balanced	< 0	> 0	< 0	0.0000	0.73	0.73	И
High	Balanced	< 0	> 0	< 0	0.0003	0.78	0.81	И

3.3. Kuznets Curve Approach Based on Agricultural N_2O

The fixed effects panel data estimation results for agricultural nitrous oxide (N_2O) emissions presented in Table 7 reveal that different Environmental Kuznets Curve patterns emerge across country groups. For the Arab World, the Euro Area, the OECD, and the World as a whole, the coefficient structure $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$ indicates an N shaped EKC. In this pattern, agricultural N_2O emissions initially decrease with rising income, then increase again, and after surpassing a certain threshold, decline one more. This suggests that environmental pressure follows a fluctuating trajectory with respect to income growth, implying that environmental policies and technological transitions do not exhibit continuity within these country groups.

For the Europe and Central Asia group, however, the model reveals a classical U shaped curve. In this case, agricultural N_2O emissions initially increase but begin to decline after a certain income level is reached. This indicates that this region, classified among developing countries, has reached a turning point in terms of environmental sustainability, where environmental pressures begin to decrease as income rises.

In the European Union, East Asia and Pacific countries, the coefficient structure, $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 = 0$, corresponds to the classical inverted U shaped EKC. This indicates that emissions increase during the early stages of economic growth but later decline due to the adoption of environmentally friendly technologies, environmental regulations, and heightened public awareness. This pattern suggests that environmental consciousness and green investments are stronger and more effectively implemented in these regions.

For the IBRD group, the results align with the classical inverted U shaped pattern, indicating that economic growth initially increases environmental impact but later contributes to its reduction. The robustness of the model is supported by the large sample size and the strong reliability of the data ($R^2 = 0.81$, adjusted $R^2 = 0.83$).

Overall, the findings show that in more developed regions, such as the European Union, the IBRD group, and East Asia and Pacific, the inverted U shaped pattern is more prominent, whereas in regions with low or middle levels of development, such as the Arab World, the Euro Area and the OECD, the environmental curve tends to take a more complex, multi-phase N shaped form. This indicates that environmental sustainability varies depending on income level, policy continuity, and technological adaptation.

Panel data estimates and results for agricultural N_2O based on income groups are presented in Table 8. For low income countries, the coefficients $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 < 0$ indicate an N shaped EKC. In this group, emissions initially increase with economic growth, then decline, but eventually show a renewed upward trend. This suggests that environmental improvements are not sustained and that the effects of policy and technological interventions remain limited.

Similarly, in the middle income group, the coefficient structure $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$ also reflects an N shaped EKC pattern. This indicates that economic development does not lead to a continuous improvement in environmental outcomes and that environmental pressures may rise again after certain stages of growth.

In the high income groups, the same curve structure is identified. Here too, the coefficient pattern $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$ indicates an N shaped EKC. This result shows that even in high income countries, income growth can reduce environmental impacts only up to a certain point, after which a renewed upward trend in emissions may occur.

In summary, the panel data analyses conducted for low, middle and high income countries indicate that the classical inverted U shaped EKC does not hold for agricultural N_2O emissions. Instead, an N shaped EKC is observed across all three income groups. This finding suggests that although income growth may initially reduce environmental degradation, this improvement is not sustainable, and environmental damage may increase again after certain thresholds. Therefore, this highlights that environmental sustainability depends not only on economic growth but also on the continuity of environmental management policies and the progression of technological transformation.

4. Discussion and Conclusion

In this study, the EKC hypothesis is tested using panel data analysis to explain the dynamics of environmental sustainability across different regions and income levels. The findings reveal that the classical inverted U shaped EKC does not fully hold for any country or income group. Instead, the emerge of more complex patterns, such as U shaped, N shaped and inverted N(∩) relationships, indicates that the interaction between the environment and the economy is nonlinear and multidimensional in nature.

The findings of the study show that income level is a decisive factor influencing environmental pressures, however, the direction and magnitude of this effect vary depending on the degree of development. In low income countries, economic growth generally increases environmental pollution rather than reducing it, while in middle income countries temporary improvements may occur, but environmental degradation eventually rises again. In contrast, high income countries appear capable of controlling emissions through environmental awareness, technological innovations, and effective policy instruments. Nevertheless, as observed in the inverted N patterns, this positive effect is not permanent, rising consumption and expanding production at higher income levels reintroduce environmental pressure. This indicates that sustainable growth cannot be achieved through income increases alone but must be supported by structural transformation.

The results across different country groups reveal that environmental degradation varies according to economic structure, industrial intensity, and energy policies. The inverted N patterns identified with high statistical reliability in OECD and IBRD countries indicate that environmental sustainability is fragile even in developed economies. This suggests that despite increased investment in environmentally friendly technologies, rising consumption patterns and expanding production volumes limit environmental gains. The N shaped curves observed in the East Asia and Pacific group reflect the fluctuating environmental impacts of rapid industrialization and urbanization. In contrast, the emergence of an inverted U shaped relationship in the European Union and Euro Area supports the effectiveness of environmental legislation, renewable energy policies and carbon pricing mechanisms implemented in these regions.

The analyses of agricultural CH_4 and N_2O emissions reveal significant structural challenges in controlling environmental degradation, particularly in developed countries. The use of energy intensive inputs in agricultural production, the increased consumption of chemical fertilizers, and inadequate waste management demonstrate that agricultural emissions tend to rise in parallel with income growth. Therefore, environmental sustainability policies should not be limited solely to the industrial and energy sectors, environmentally responsible production techniques in agriculture, the protection of carbon sink areas, and the adoption of bio economy based models must also be prioritized and expanded.

The existing literature lacks consensus regarding the relationship between income levels and environmental degradation. While a segment of studies confirms the classical Environmental Kuznets Curve by identifying an inverted U-shaped relationship (Bilgili et al., 2016; Hao and Liu, 2016), another group contends that this hypothesis is invalid or that the relationship follows a U-shape (Güvenek and Alptekin 2010; Ozturk and Acaravci, 2010). In more recent analyses, an N-shaped relationship—indicating that pollution rises again after a decline—has been empirically demonstrated (Abbasi et al., 2023; Narcisse et al., 2023).

The analyses results indicate that the environmental of dynamics differing across countries according to their level of development necessitate flexible and country specific strategies rather than uniform global policies. In low income countries, priority should be given to strengthening environmental infrastructure, promoting investments in energy efficiency, and enhancing environmental awareness. In middle income countries,

"green technologies" and sustainable urbanization practices compatible with growth policies should be emphasized. In high income countries, preserving environmental gains requires the implementation of circular economy practices, carbon neutral production models and behavioral policies aimed at transforming consumption patterns.

Furthermore, ensuring policy continuity and institutional coordination is essential for transforming the fluctuating trajectory of environmental degradation into a stable improvement. The fact that the EKC emerges in different forms across countries demonstrates that sustainable development goals depend not only on economic indicators but also on societal awareness, institutional capacity, and technological adaptation.

In conclusion, environmental sustainability is not a natural byproduct of economic growth, rather, it is a process that must be supported by deliberate planning, environmental regulation, and technological innovation. Although, the EKC hypothesis is partially validated in this study, the results clearly demonstrate that income growth alone does not guarantee environmental improvement. Long term environmental balance depends on the quality of economic growth, the structure of energy sources used, and the effectiveness of environmental policies. Therefore, sustainable development policies must integrate economic, social, and ecological dimensions through a holistic approach and should be designed with consideration for regional differences and local capacity levels.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	B.A.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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