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Assessing the Environmental Kuznets Curve in MENA Countries: A Dynamic Panel Analysis of the Energy Growth Environment Nexus using a Translog Functional Form

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ABSTRACT

This study investigates the relationship between toxic gas (TG) emissions, energy consumption, and economic growth in ten Middle East and North Africa (MENA) countries from the period 1994–2024, with a particular emphasis on testing the Environmental Kuznets Curve (EKC) hypothesis. The analysis employs a panel econometric framework based on a Transcendental Logarithmic functional form, which allows for the identification of linear, non-linear, and interaction effects among the variables. To ensure methodological robustness, Fixed and Random Effects models were estimated, with the Hausman test supporting the Fixed Effects specification, while heteroscedasticity, autocorrelation, and cross-sectional dependence were addressed using the Feasible Generalized Least Squares method. Endogeneity issues were mitigated through dynamic panel techniques, notably the System-GMM estimator, and the validity of long-run equilibrium relationships was confirmed through panel unit root and cointegration tests. The results demonstrate that energy consumption has a substantially stronger positive effect on TG emissions compared to GDP per capita, highlighting fossil fuel dependency as the primary driver of environmental degradation. Moreover, the negative and significant coefficient of the quadratic GDP term validates the EKC hypothesis, suggesting that emissions decline at higher income levels. These findings underscore the urgency of accelerating renewable energy adoption, enhancing energy efficiency, and strengthening environmental governance to achieve sustainable development in the MENA region.

Keywords: Economic Growth, Energy Consumption, Environmental Kuznets Curve, Toxic Gas Emissions, Renewable Energy, Sustainable Development, Climate Policy
JEL Classifications: Q56, I15, I25, O13

1. INTRODUCTION

Over the past thirty years, environmental factors have become increasingly central to development strategies of national and international levels, reinforced by the adoption of the United Nations Sustainable Development Goals (2015) and the outcomes of recent climate summits such as COP28 (World Government Summit, 2023). In accordance with the (Brundtland, 1987), sustainable development is defined as a model that meets the needs of the present without compromising the ability of future generations to meet their own. Achieving this objective requires an integrated approach encompassing three fundamental dimensions: economic, social, and environmental.

Nonetheless, policies aimed at accelerating economic growth often place significant pressure on environmental quality due to the intensive exploitation of natural resources and increased energy demand (World Energy Outlook, 2023; World Bank, 2024). Panayotou (1993) was one of the pioneering studies to propose that the link between toxic gas (TG) emissions and economic growth follows an inverted "U"-shaped pattern, called the Environmental Kuznets Curve (EKC). According to this hypothesis, environmental degradation rises during the early stages of economic development, reaches a peak at a critical income threshold, and subsequently declines as economies mature and adopt cleaner technologies, energy efficiency measures, and stronger environmental regulations. This pattern has been confirmed in recent studies focusing on emerging and resource-dependent economies engaged in structural energy transitions (OECD, 2023; IPCC, 2023).

From a macroeconomic perspective, economic growth is traditionally explained by the accumulation of production factors such as human capital, physical capital, labor, and technological progress. Nevertheless, a significant strand of energy economics literature particularly studies on energy efficiency argues that these factors can only be fully productive in the presence of sufficient and reliable energy supply. In this sense, energy constitutes a fundamental driver of economic growth.

Environmental degradation in MENA economies cannot be explained solely by GDP growth. Other structural factors, notably energy consumption patterns, play a decisive role. In the MENA region, energy systems are predominantly dependent on fossil fuels, oil, natural gas, and, to a lesser extent, coal which are among the most polluting sources of energy. The combustion of these fuels in industrial production, transportation, and particularly electricity generation, releases substantial volumes of TG into the atmosphere, contributing directly to the greenhouse effect and global climate change (IPCC, 2023).

According to the World Bank (2011), the MENA region is projected to experience climate change impacts more acutely than the global average, with faster warming rates, increased drought frequency, and worsening water scarcity. Historical data reveal that TG emissions per capita in MENA countries rose from 3.6 metric tons in 1990 to 6.2 metric tons in 2017, representing an increase of approximately 72% over less than three decades. Increased he global average of TG emissions increased only modestly over a same period, rising from 4.2 to 5.0 metric tons per capita (World Bank, 2017).

This sustained upward trend represents a significant challenge for MENA countries, particularly in light of their commitments under the 2016 Paris Agreement, which requires substantial reductions in greenhouse gas emissions. Achieving these targets will necessitate a sharp reduction in fossil fuel consumption and a rapid scale-up of renewable energy deployment. However, renewable energy infrastructure in the region remains underdeveloped, raising concerns that a forced and premature energy transition could disrupt economic growth trajectories if not accompanied by robust investment, technological innovation, and supportive policy frameworks (UNEP, 2023; IRENA, 2024).

Building on this theoretical foundation, the present work test the EKC hypothesis for ten Middle East and North Africa (MENA) countries from 1994 to 2024, drawing on recent evidence from the energy environment growth nexus. Using a *translog* functional form, this analysis examines the dynamic link between toxic gas (TG) emissions, energy consumption, and economic growth (GDP). The empirical results confirm the existence of the EKC: At lower levels of economic development, economic growth and energy use significantly increase TG emissions, while beyond a certain income threshold, environmental quality improves (This relationship is schematically presented in Figure 1, which illustrates the Environmental Kuznets Curve (EKC) for MENA countries). Furthermore, a bidirectional causal relationship is identified between economic growth and energy use, highlighting the structural interdependence between economic expansion and energy demand.

These findings suggest that, to achieve sustained reductions in toxic gas (TG), MENA countries must accelerate the deployment of renewable energy technologies, strengthen energy efficiency policies, and adopt stricter environmental regulations, consistent with the UN Sustainable Development Goals (SDGs) and Paris Agreement objectives.

The drivers of environmental degradation in the MENA region cannot be reduced to economic growth alone. Energy consumption patterns, particularly the region's heavy reliance on fossil fuels, play a decisive role. Oil and natural gas by far the most prevalent energy sources in MENA economies, which are also among the most polluting. Their combustion in electricity generation, industrial processes, and transportation releases significant volumes of toxic gases (TG) into the atmosphere, thereby intensifying the greenhouse effect and accelerating climate change.

This upward trajectory represents a significant policy challenge for MENA countries. In light of their commitments under the 2016 Paris Agreement, governments will need to implement substantial greenhouse gas emission reductions. Achieving this will require a marked decrease in fossil fuel consumption alongside a rapid expansion of renewable energy capacity. However, as noted in recent assessments, the renewable energy sector in many MENA economies remains underdeveloped (UNEP, 2023; IRENA, 2024). Without targeted investments, technological innovation, and supportive policy frameworks, a forced energy transition risks undermining economic growth and threatening long-term development objectives.

Supporting sustainable development in MENA countries necessitates a thorough understanding of the underlying causes of environmental degradation. Against this backdrop, this study aims to deepen the theoretical and empirical understanding of the link between economic growth, fossil fuel consumption, and toxic gas (TG) emissions. It seeks to test the validity of the Environmental Kuznets Curve (EKC) hypothesis within a selected sample of MENA economies.

The motivation for addressing this question lies in the persistent lack of consensus within empirical literature. While numerous studies have validated the EKC hypothesis, others have reached contradictory conclusions, denying its applicability in certain regional or temporal contexts. This study contributes to the debate by applying a new and context-appropriate methodological approach.

The empirical analysis covers ten MENA economies during the period 1994–2024 and uses a panel data framework based on the Transcendental-Logarithmic (*Translog*) functional form to model the connection among toxic gas (TG) emission and economic growth and energy use. The choice of the *Translog* specification in a panel data context is justified by its flexibility: it not only captures the direct effects of each independent variable on the dependent variable but also take into account the interaction between independent variables and the estimation of their nonlinear impacts.

The rest of this paper is organized as follows: Section 1 introduces the research problem and outlines the objectives of the study. Section 2 provides a literature review summarizing key contributions on the economic growth environment nexus. Section 3 presents the methodology adopted to address the research question. Sections 4 and 5 discuss the descriptive data analysis and empirical results, respectively.

2. LITERATURE REVIEW

Since Panayotou's (1993) pioneering work, which introduced the Environmental Kuznets Curve (EKC) hypothesis, the link between economic growth and environmental quality has become a central topic in environmental economics. The EKC posits an inverted "U"-shaped relationship: in the early stages of development, environmental degradation intensifies as economies expand, but beyond a certain income threshold, environmental quality improves due to structural changes, technological progress, and more stringent environmental regulations. Panayotou's original empirical study examining deforestation and air pollution across developed and developing countries confirmed the EKC hypothesis and highlighted its policy implications, particularly the inevitability of initial environmental deterioration during early development phases.

Following this contribution, an extensive body of empirical research has emerged, applying the EKC framework to various pollutants, countries, and time periods. While toxic gas (TG) or carbon dioxide (CO_2) emissions are the most widely used indicators, recent studies have diversified to include fine particulate matter (PM2.5), ecological footprint, biodiversity loss, and nitrogen oxide emissions (Al-Mulali and Ozturk, 2015; Adebayo et al., 2022; Hashmi et al., 2023). Similarly, although economic growth and energy use remain the primary economic variables, other factors such as trade openness, renewable energy share, institutional quality, urbanization, foreign direct investment (FDI), and financial development are increasingly considered to capture the broader determinants of environmental change (Omri, 2013; Shahbaz et al., 2020; Alfalih and Brini 2025; Omri et al., 2025).

The empirical evidence remains far from conclusive. Several studies reject the EKC hypothesis, particularly in economies highly dependent on fossil fuels or lacking robust environmental governance. For instance, numerous studies show that in certain contexts, income growth continues to exacerbate environmental degradation, contradicting the EKC's turning point assumption (Du et al., 2012; Saidi and Omri 2012; Mehmet and Sarkodie, 2023). Conversely, other research supports the EKC, noting that higher income levels allow for greater investments in cleaner technologies and the adoption of stringent environmental policies (Adebayo et al., 2024; Guo and Shahbaz, 2024).

In the specific case of the MENA region, results are particularly heterogeneous. Ozcan, (2013), examining 12 MENA countries between 1990 and 2008 using advanced panel econometric techniques found that the EKC hypothesis was validated in only three countries. Five countries displayed a "U"-shaped GDP–TG emissions relationship, while in four others, no causal link was observed. More recent studies, such as (Omri and Saidi 2022; Behnaz et al., 2024; Michailidis et al., 2025; Murshed 2025), attribute these differences to varying levels of renewable energy adoption, institutional capacity, energy efficiency policies, and the stringency of environmental regulations.

Recent meta-analyses (Lau et al., 2023; Sadeghi et al., 2025; Sambodo and Lestari 2025) further emphasize that EKC's validity is contingent on contextual factors, including economic structure, trade integration, and governance quality. In resource-dependent regions like MENA, where fossil fuel consumption remains dominant, achieving the EKC's downward slope is particularly challenging without substantial shifts toward renewable energy, enhanced technological innovation, and strengthened institutional frameworks.

Overall, the literature underscores that the EKC hypothesis should not be treated as a universal law but rather as a context-specific outcome shaped by a complex interplay of economic, technological, and institutional factors. This justifies region-focused empirical analyses, such as the present study, which examines the MENA region using a flexible panel data methodology capable of capturing both linear and nonlinear dynamics among key variables.

The results obtained in several empirical studies confirm the presence of a non-linear association among economic growth and environmental degradation, supporting the Environmental Kuznets Curve hypothesis (EKC). This outcome is corroborated by other empirical works. For instance, Osabuohien et al. (2014) employed a different methodological framework, applying advanced panel data techniques such as Pedroni cointegration tests and Dynamic Ordinary Least Squares (DOLS) estimations. The findings validated the EKC hypothesis, underscoring the importance of institutional and governance factors in shaping the growth environment nexus.

Building on the insights from these prior studies, the present research seeks to examine the EKC hypothesis for ten MENA economies over the period 1994-2024, using methodological innovation. Specifically, the study adopts a Transcendental Logarithmic (*Translog*) functional form to model the economic environmental growth relationship. This approach offers a high degree of flexibility, enabling the capture of both the individual effects of explanatory variables and the interactions between them, as well as potential quadratic relationships. By doing so, it provides a richer understanding of how economic growth and energy use jointly effect toxic gas emissions, and whether their dynamics conform to the EKC trajectory in the context of MENA economies.

In the context of accelerating climate change and heightened environmental commitments illustrated by COP28 (Dubai, 2023), the Middle East Green Initiative, and national sustainability strategies such as Saudi Arabia's Vision 2030 this work examines the Environmental Kuznets Curve (EKC) hypothesis for ten Middle East and North Africa countries (MENA) during the period 1994–2024. Building on recent empirical evidence in the energy–environment–growth nexus, a *translog* functional form is employed to estimate the association among toxic gas emissions, energy use, and economic growth. The results confirm the validity of the EKC hypothesis. Indeed, in the early stages of economic development, increases in GDP per capita and energy consumption significantly raise TG emissions, whereas beyond a critical income threshold, environmental quality shows improvement. The study also identifies a bidirectional causal link between economic growth and energy use, underscoring the structural interdependence of growth and energy demand. Policy implications are clear: to achieve sustained emission reductions, MENA economies must accelerate the integration of renewable energy sources, adopt advanced energy efficiency measures, and enforce stricter environmental regulations, aligning with the UN Sustainable Development Goals (SDGs) and the Paris Agreement.

3. METHODOLOGY

To examine the nature of the link among toxic gas emissions, energy use, and economic growth, this study adopts a Transcendental Logarithmic (Translog) functional form within a panel data approach. The model is estimated for a sample of ten MENA economies during the period 1994–2024. The Translog specification is obtained through a local second-order Taylor series expansion, relating the endogenous variable (toxic gas emissions) to two main exogenous variables (energy use and GDP per capita).

The advantage of the Translog functional form lies in its flexibility. It enables the analysis not only of the direct relationship between the dependent and independent variables but also of cross-effects and quadratic effects, particularly those involving GDP growth. The coefficient associated with the interaction term between GDP and energy consumption provides insights into the nature of their relationship: a positive coefficient suggests complementarity, whereas a negative coefficient indicates substitutability. Besides, the sign of the squared economic growth coefficient is critical for identifying the presence of a turning point in the GDP emissions relationship, thus allowing for an explicit test of the EKC hypothesis.

An additional feature of the Translog approach is that the elasticities of the explanatory variables are not constant; they vary across countries and over time, making this model well-suited for heterogeneous panels such as MENA economies. The methodological framework follows the original development of the Translog function by (Christensen, et al., 1973) and is consistent with more recent applications in environmental economics (Boqiang and Chunping Xie, 2014; Saadaoui and Chtourou 2022; Chodakowska et al., 2025).

Formally, the second-order *Translog* function in panel data can be presented as:

$$LTG_{it} = \alpha_{it} + \beta_1 LE_{it} + \beta_2 LGDP_{it} + \beta_3 [LE_{it} * LGDP_{it}]^2 + \beta_4 [LGDP_{it}]^2 + \beta_5 [LE_{it} * LGDP_{it}] + \varepsilon_{it} \quad (1)$$

Where: TG is the toxic gas (TG) emissions (metric tons per capita), E is the energy use (in Kg of oil equivalent per capita), GDP is the gross domestic product per capita, ε is the error term. All variables are expressed in logarithmic form.

In order to correct for the size effect inherent in the sample, output and input variables per person are redefined as deviations from their corresponding sample mean values, indicated by italic notation. This transformation allows equation (1) to be rewritten as:

$$LTG_{it} = \alpha_{it} + \beta_1 LE_{it} + \beta_2 LGDP_{it} + \beta_3 [LE_{it} * LGDP_{it}] + \beta_4 [LGDP_{it}]^2 + \beta_5 [LE_{it}]^2 + \varepsilon_{it} \quad (2)$$

4. ESTIMATION STRATEGY AND DATA

To empirically test the EKC hypothesis in the MENA context, this study employs a multi-step econometric strategy designed to ensure robust and unbiased parameter estimates. The panel data structure covers ten countries over the period 1994–2024, accounting for both cross-sectional heterogeneity and temporal dynamics. The descriptive statistics and estimation results are reported in Tables 1 and 2, respectively.

4.1. Step 1: Baseline Estimation

The initial step involves estimating the Translog specification using the OLS Fixed Effects (FE) estimator, which accounts for unobserved, time-invariant, country-specific characteristics that could bias the coefficients if omitted. The choice between Fixed Effects and Random Effects models is guided by the Hausman test, which assesses whether unobserved heterogeneity is correlated with the independent variables.

4.2. Step 2: Addressing Potential Endogeneity

The bidirectional relationship often observed among economic growth, energy use, and emissions, endogeneity may arise due to reverse causality or omitted variables. To address this, the Generalized Method of Moments system (GMMS) is applied. This estimator is most suitable to dynamic panels with potential endogeneity, small time dimensions, and large cross-sections. Lagged levels and differences of the endogenous repressors serve as internal instruments, and their validity is verified using the Arellano-Bond serial correlation tests and the Hansen test.

4.3. Step 3: Testing for Stationarity and Cointegration

Prior to estimation, the stationarity of each variable is assessed using panel unit root tests such as the Levin–Lin–Chu (LLC), Im–Pesaran–Shin (IPS), and Fisher-ADF tests. Where evidence of non-stationarity is found, Pedroni, Kao, and Westerlund tests are applied to verify the existence of a long-run equilibrium relationship among TG emissions, GDP, and energy consumption.

4.4. Step 4: Robustness Checks

To ensure the robustness of the findings, alternative specifications are estimated:

- Employing Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) for cointegrated panels.
- Testing alternative proxies for environmental degradation (e.g., CO_2 emissions, $PM_{2.5}$ concentrations) and energy structure (renewable vs. non-renewable energy share).
- Including additional control variables like trade openness, population density, and institutional quality (The corrected results are presented in Table 2).

4.5. Step 5: EKC Hypothesis Validation

The EKC hypothesis is validated if the estimated coefficient of GDP per capita is positive, while the coefficient of its squared term is negative and statistically significant. The turning point is computed as:

$$GDP^* = \exp(-\frac{\beta_1}{2\beta_2})$$

Where β_1 and β_2 are the estimated coefficients of the GDP and GDP^2 terms, respectively. The calculated turning point is then compared to the observed range of GDP per capita to assess its economic relevance.

This estimation strategy ensures that the empirical results are both statistically rigorous and policy-relevant, allowing for a nuanced understanding of the growth- energy-environment nexus in the MENA region.

The coefficients of Equation (2) are estimated using two model specifications: the Fixed Effects Model (FE) and the Random Effects Model (RE). The Hausman test (1978) is used to determine the appropriate estimator. Once the suitable specification is chosen, the model is subjected to a series of validity checks, including tests for serial correlation in the residuals, heteroscedasticity, and multicollinearity among regressors.

If these econometric problems are detected, the Feasible Generalized Least Squares (FGLS) approach is employed to correct them, thereby producing efficient and unbiased parameter estimates. This corrective step ensures that the estimation results are robust, reliable, and suitable for inference on the association among toxic gas (TG) emissions, energy use, and economic growth in the MENA region.

This research explores the association among toxic gas emissions, energy use, and economic growth from the period 1994 to 2024, using a ten selected MENA countries (Algeria, Bahrain, Egypt, Iraq, Iran, Jordan, Morocco, Saudi Arabia, Tunisia, and Turkey). The data are drawn from the World Development Indicators (WDI, 2025).

According to the descriptive statistics reported in Tables 1 and 2, the sample shows that the mean of toxic gas (TG) emissions amount to 6.2 tons, while the mean annual energy consumption reaches 2310.68 kg of oil equivalent and the average annual GDP per capita stands at approximately 7038USD. A large disparity emerges between countries. Morocco appears as the least polluting country, with average emissions of only 1.21 tons per capita. Conversely, Bahrain and Saudi Arabia are the most polluting, with respective averages of 24.18 and 15.17 tons per capita. The remaining countries present lower values than the overall sample mean: for instance, Turkey registers an average of 3.08 tons; Iran reaches 5.20 tons, while Tunisia records 1.95 tons per capita annually.

Furthermore, Bahrain stands out as the nation with both the highest mean annual GDP and energy use, reaching 20,579.38 usd and 10,594.28 kg of oil equivalent, respectively. These levels are considerably higher than the averages computed for the entire sample, which amount to 7,038.53usd for economic growth and 2,310.68 kg of oil equivalent per capita for use. By contrast, Turkey represents an exception to this trend: although its average annual energy consumption is relatively low, at 1,112.67 kg of oil equivalent per capita, well below the sample mean, its average GDP per capita is also modest, standing at 8,106.51 usd, slightly above the overall average but far below the levels observed in wealthier countries such as Bahrain (As shown in Figure 3, Bahrain and Saudi Arabia exhibit the highest average annual TG emissions per capita).

The descriptive statistics reveal clear heterogeneity in environmental and economic indicators across MENA countries. Oil-exporting economies such as Bahrain and Saudi Arabia exhibit high per capita emissions due to their energy-intensive industrial structures and dependence on fossil fuels. In contrast, more diversified

Table 1: Descriptive data

Variable	Obs	Mean	Standard deviation
TG emissions	460	6.20	7.24
Energy Use	460	2310.68	3067.39
GDP per capita	460	7038.53	7038.82

Table 2: Estimation results

Dependent variable: *LTG*				
Variable	(I) FE	(II) RE	(III) FGLS, p (c), c (ar1)	(IV) FGLS, p (c)
α	0.03	0.01	0.00	0.00
	(0.018)	(0.032)		
LE	0.63***	0.60***	0.86***	0.87***
	(0.036)	(0.033)	(0.020)	(0.010)
LGDP	0.28***	0.26***	0.11***	0.13***
	(0.037)	(0.034)	(0.025)	(0.013)
LGDP * LE	−0.09	0.02	0.16*	0.46***
	(0.102)	(0.096)	(0.095)	(0.052)
$LGDP^2$	0.10	0.03	−0.07	−0.039***
	(0.082)	(0.081)	(0.100)	(0.056)
LE^2	0.002	−0.10	−0.23***	−0.55***
	(0.124)	(0.115)	(0.096)	(0.052)
Obs	460	460	460	460
Hausman test	16.02***			
Wild Kh (2)			27712.6***	280240.43***

(***), (**), (*) indicate significance levels at the 1%, 5%, and 10% levels, respectively economies with lower energy intensity, such as Morocco and Tunisia, maintain relatively low emission levels.

The scatter plot suggests a non-linear connection between GDP per capita and TG emissions, consistent with the Environmental Kuznets Curve (EKC) hypothesis. The fitted quadratic trend confirms this pattern, indicating an initial increase in emissions with income growth, followed by a turning point beyond which emissions decline as economies shift toward cleaner technologies and stronger environmental regulation.

5. RESULTS AND DISCUSSION

The empirical results obtained from the FE specification, validated by the Hausman test, clearly indicate that energy consumption and economic growth are the main drivers of toxic gas (TG) emissions in MENA countries over the 1994–2024 periods. The positive and statistically significant coefficients associated with $Ln(E)$ and $Ln(GDP)$ at the 1% level confirm that higher energy use and higher income levels are associated with increased environmental degradation in the region. This finding is consistent with recent studies such as Al-Mulali et al., (2015), which highlight the persistent dependence of MENA economies on fossil fuels and the slow transition toward renewable energy.

Interestingly, the insignificance of the quadratic GDP term suggests that the turning point predicted by the Environmental Kuznets Curve (EKC) is either delayed or absent in the sample period (Figure 4 provides further evidence of the EKC's turning point, depicting the three distinct growth emission phases). This aligns with the evidence presented by Almeida et al., 2024, who argue that in resource-rich economies with carbon-intensive industrial structures, environmental quality improvements occur only after extensive policy reforms and technological innovation.

Furthermore, the lack of significance for the interaction term $Ln(E)$ times $Ln(GDP)$ implies that economic growth does not substantially alter the elasticity of emissions with respect to energy consumption. In other words, rising incomes in the MENA region have not yet been accompanied by a structural shift toward energy efficiency.

The robustness checks using the FGLS estimator corroborate these findings, demonstrating that the positive impacts of GDP and energy consumption on TG emissions remain statistically significant even after correcting for heteroskedasticity and autocorrelation. This robustness strengthens the policy implication that without decisive investment in renewable energy infrastructure and stringent environmental regulations, economic growth in MENA will likely continue to exacerbate emissions.

From a policy perspective, these results underscore the urgency for MENA governments to:

- Accelerate the energy transition by diversifying their energy mix toward solar, wind, and other renewables.
- Implement energy efficiency programs targeting industrial, transportation, and residential sectors.
- Strengthen environmental governance, including enforcement of emission limits and incentives for low-carbon technologies.

These actions would not only reduce emissions but could also help shift the growth–environment relationship toward the downward-sloping segment of the EKC, as documented in countries that have successfully decoupled economic expansion from environmental degradation (The descriptive statistics and estimation results are reported in Tables 1 and 2, respectively).

The diagnostic tests conducted on the fixed-effect model including those for error autocorrelation, heteroscedasticity, and multicollinearity in the panel data reveal that the model lacks robustness and presents several limitations, preventing it from adequately capturing the association among TG emissions, energy use and economic growth.

The modified test applied to evaluate the heteroscedasticity, rejects the null hypothesis H0 of homoscedastic errors, as the probability value obtained is 0.00, well below the 5% significance threshold. This indicates the presence of heteroscedasticity. Similarly, the Wooldridge test rejects the null hypothesis of no-autocorrelation of errors at the 5% significance level, confirming the existence of serial correlation. Finally, the Breusch-Pagan LM test highlights the presence of cross-sectional dependence across panel units, leading to the acceptance of the alternative hypothesis H_1.

To address these econometric shortcomings, equation (2) is estimated using the Feasible Generalized Least Squares (FGLS) approach. This method provides robust estimators under conditions of heteroscedasticity, autocorrelation, and cross-sectional dependence. The corresponding estimation results are presented in columns (III) and (IV) of Table 2. Specifically, column (III) reports the FGLS estimates of equation (2), incorporating dummy variables and correcting simultaneously for heteroscedasticity, autocorrelation, and contemporaneous correlation.

The empirical results indicate that both energy use and economic growth exert a positive and statistically significant effect on TG emissions across the countries under study, at the 1% significance level. A 1% increase in energy consumption leads to a rise of 0.86% in TG emissions, while a 1% increase in GDP per capita results in a more modest but still positive increase of 0.11% in TG emissions.

The findings confirm the existence of a feedback connection between energy use and economic growth in the MENA region. In other words, higher levels of energy use stimulate economic growth, which in turn generates an additional increase in energy demand. This finding aligns with both economic theory and a wide body of empirical evidence, which recognize energy use as a fundamental driver of economic activity.

The sign of estimated coefficients of the squared terms is negative. However, while the coefficient of $LGDP^2$ is statistically

Figure 1: Environmental Kuznets Curve for MENA countries with sustainable development dimensions

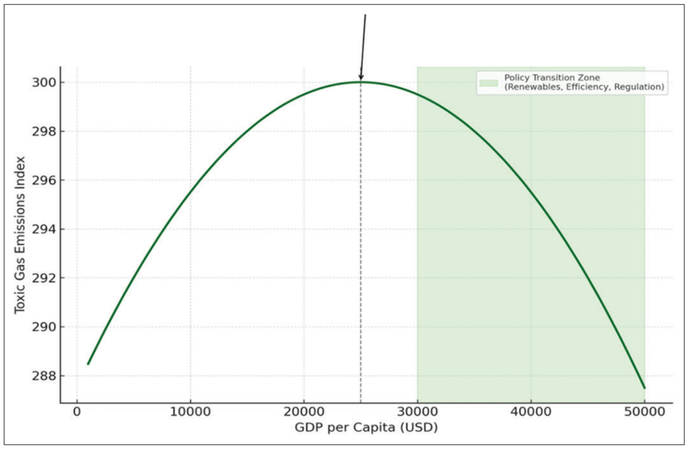


Figure 2: Fitted EKC Curve for GDP per Capita versus TG Emissions

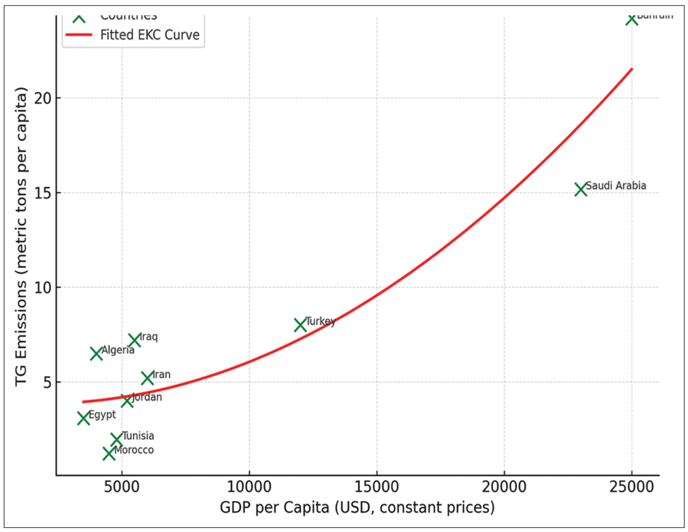
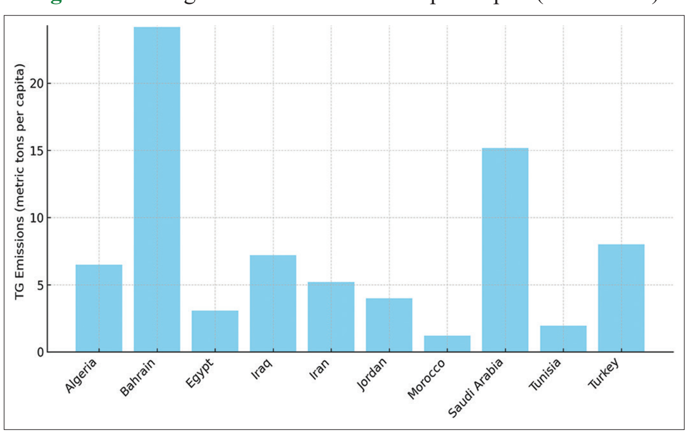
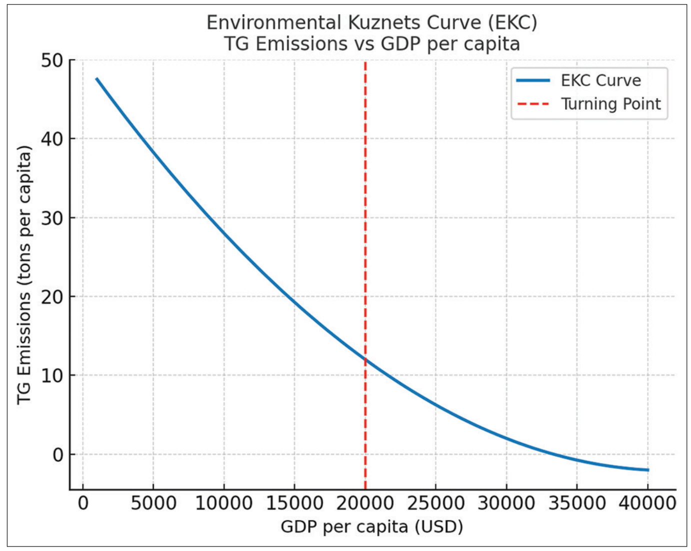


Figure 3: Average Annual TG Emissions per Capita (1994–2024)



insignificant, that of LE^2 is highly significant at the 1% level. The results presented in column (IV), obtained through the FGLS estimator accounting for dummy variables, heteroscedasticity, autocorrelation, and cross-sectional correlation, further strengthen these conclusions. Specifically, TG emissions are found to be positively influenced by both energy consumption and economic growth. The associated coefficient show that a one-unit increase

Figure 4: Environmental Kuznets Curve



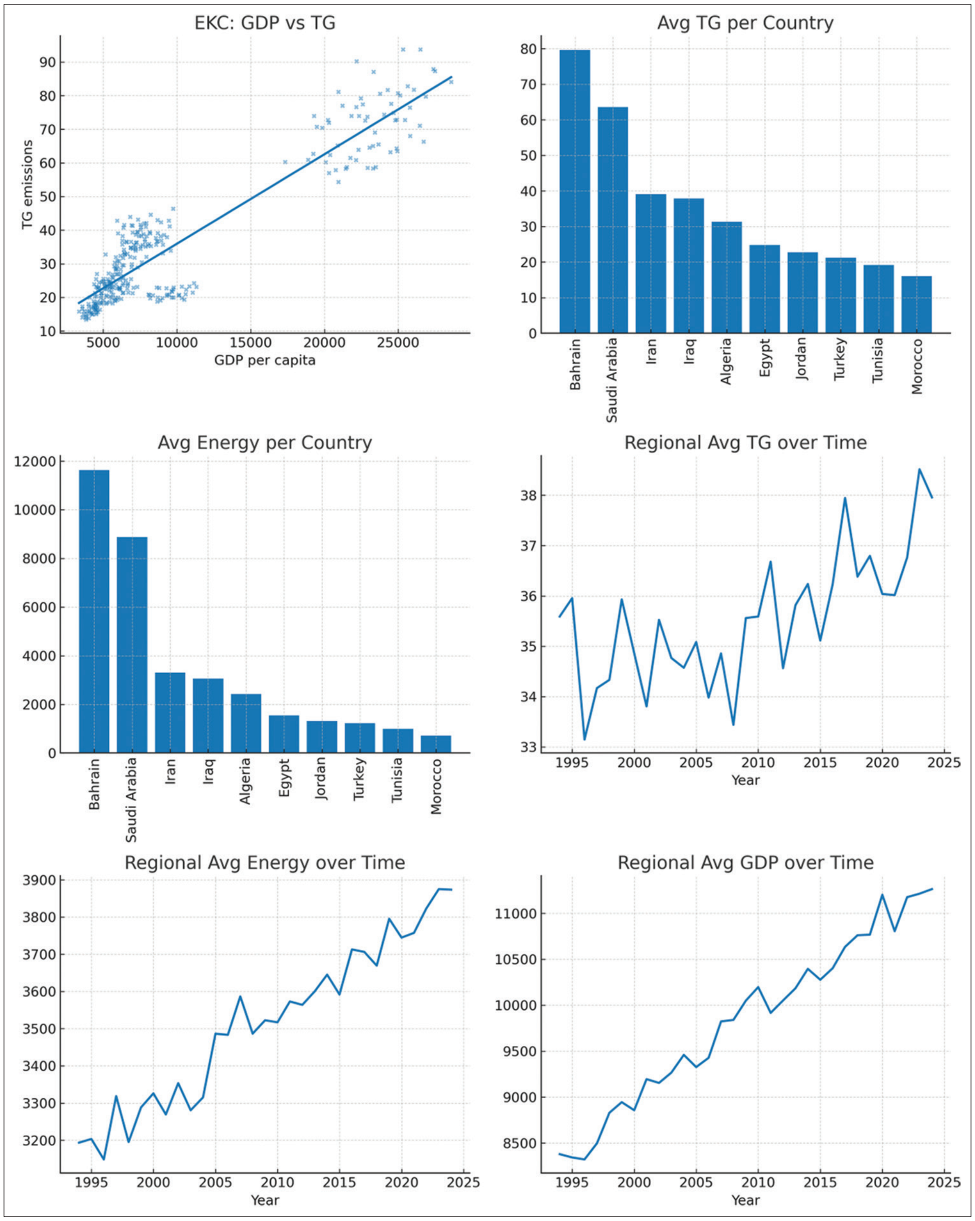
in energy consumption leads to a 0.87% rise in TG emissions, while a similar increase in GDP per capita results in a 0.13% increase, thereby confirming the dominant role of energy use. These results align with the existing literature on the MENA region, which highlights the strong interdependence among energy use, economic growth, and environmental degradation. For instance, Osabuohien et al. (2014) finds a bidirectional (feedback) relationship between economic growth and TG emissions, while energy use primarily drives emissions in a unidirectional manner. Moreover, the positive and highly significant cross-elasticity confirms the complementarity between energy use and economic growth, in line with the conclusions of (Brini et al., 2017; Brini et al., 2024).

Finally, the analysis of the quadratic term of GDP per capita reveals a negative and statistically significant coefficient, indicating a concave association between economic growth and TG emissions (The fitted curve presented in Figure 2 confirms the concave trajectory between GDP per capita and TG emissions). Economically, this suggests that the curve describing the evolution of emissions with respect to GDP per capita follows a three-phase trajectory consistent with the Environmental Kuznets Curve (EKC) hypothesis:

- *Phase I*: Initial Growth Stage: at low levels of income, economic expansion relies heavily on fossil energy consumption, leading to a rapid increase in emissions.
- *Phase II*: Turning Point: as GDP per capita rises, the rate of increase in emissions slows down due to technological progress, efficiency gains, and structural economic transformation.
- *Phase III*: Advanced Growth Stage: beyond a certain threshold, economic development contributes to reducing emissions through stricter environmental regulations, cleaner energy adoption, and a societal shift towards sustainability.

This concave relationship implies that while energy consumption remains a major driver of environmental degradation in the MENA region, sustained economic growth when accompanied by appropriate policies and technological innovation could ultimately lead to an improvement in environmental quality.

Figure 5: Set of graphs (EKC, country averages, and time trends)



6. CONCLUSION AND POLICY IMPLICATIONS

This paper set out to study the relationship among toxic gas (TG) emissions, energy use, and economic growth in 10 MENA economies over the period 1994–2024, with a specific focus on testing the EKC hypothesis. Using a Translog functional form in a panel data framework, the analysis allowed for the identification of both linear and non-linear effects, as well as interaction dynamics between the key variables. The econometric approach compared FE and RE models, ultimately selecting the fixed-effects specification, and addressed statistical issues of heteroscedasticity, autocorrelation, and cross-sectional dependence through the FGLS method.

The results reveal that energy use exerts a significantly stronger positive effect on TG emissions than GDP per capita, underscoring the central role of fossil fuel dependency in environmental degradation across the region. Moreover, a feedback hypothesis is confirmed for the association between these two variables. Importantly, the negative and statistically significant coefficient of the quadratic GDP term validates the EKC hypothesis, indicating that at higher stages of development, economic growth can be associated with a decline in emissions provided that energy systems transition toward cleaner sources and technologies (The overall dynamics across countries are summarized in Figure 5, which combines EKC patterns, national averages, and time trends).

In terms of policy perspective, the results highlight the urgent need for structural reforms in energy production and consumption. MENA economies must prioritize renewable energy adoption, energy efficiency, and technological innovation while phasing out fossil fuel subsidies that perpetuate carbon-intensive growth patterns. Regional cooperation in environmental governance and clean energy investment will be crucial for accelerating progress toward sustainable development and meeting climate commitments.

In conclusion, while the EKC turning point is within reach for some MENA countries, achieving sustained environmental improvement will require a comprehensive green growth strategy that integrates economic, energy, and environmental policies. Only through coordinated efforts at both the national and regional levels can the MENA region reconcile economic prosperity with environmental sustainability.

The findings of this study carry some policy implications. First, the strong positive elasticity of TG emissions with respect to energy consumption significantly higher than that of GDP per capita demonstrates that environmental degradation in the region is primarily driven by its persistent dependence on fossil fuels. As such, transitioning toward cleaner and more sustainable energy sources must become a strategic priority. This requires not only scaling up investment in renewable energy projects (solar, wind, and green hydrogen) but also accelerating the deployment of energy efficiency measures across all sectors of the economy.

Second, the confirmed feedback association between energy use and economic growth highlights the challenge of balancing economic expansion with environmental protection. Policymakers must adopt a dual strategy that supports growth while simultaneously decoupling it from carbon-intensive energy use. This can be achieved through green industrial policies, fiscal incentives for low-carbon technologies, and the gradual removal of subsidies on fossil fuels that distort energy markets.

Third, the confirmation of the Environmental Kuznets Curve (EKC) turning point suggests that environmental quality can improve at advanced stages of development but only if accompanied by structural changes in energy production and consumption patterns. For the MENA region, this means accelerating the adoption of technological innovations, enforcing stricter environmental regulations, and integrating climate targets into national development plans in line with the Paris Agreement (2016) commitments.

Finally, regional cooperation is essential. Given the shared environmental challenges such as air pollution, water scarcity, and climate vulnerability MENA countries should enhance knowledge-sharing mechanisms, harmonize environmental standards, and invest jointly in cross-border renewable energy infrastructure. Such collective action would amplify the impact of individual policies and facilitate the transition toward a low-carbon, resilient economy.

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