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Economic Growth and Environmental Degradation in Oman: Testing the Environmental Kuznets Curve Hypothesis Using Time Series Analysis

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ABSTRACT

This study investigates the validity of the Environmental Kuznets Curve (EKC) hypothesis in Oman, examining the relationship between economic growth and CO_2 emissions from 1998 to 2022. Using annual time series data, the study employs unit root tests, vector autoregressive (VAR) models, and Granger causality tests to analyze the dynamics between GDP per capita and environmental degradation. The results reveal that Oman is situated on the upward slope of the EKC, indicating a positive correlation between income levels and CO_2 emissions. Both the quadratic and cubic EKC models demonstrate a strong goodness of fit, with the cubic model providing a more nuanced understanding of the non-linear relationship. The Granger causality tests confirm unidirectional causality from economic growth to emissions, while impulse response analysis suggests that Oman has not yet reached the turning point where environmental degradation begins to decline. These findings align with previous research on developing economies, highlighting the challenges of balancing economic growth with environmental sustainability. The study concludes that proactive policy measures, such as investments in renewable energy and stricter environmental regulations, are essential for Oman to transition toward sustainable development. The implications of this research extend to policymakers and stakeholders, emphasizing the need for integrated strategies to achieve the goals of Oman's Vision 2040 while addressing global climate change challenges.

Keywords: Environmental Kuznets Curve, CO_2 Emissions, Economic Growth, Oman, VAR Model, Sustainability
JEL Classifications: Q53, Q56, C32, 044

1. INTRODUCTION

The connection between levels of CO_2 emissions and the extent of environmental degradation has been extensively examined in recent decades, particularly as global warming has emerged as a critical issue (Begum et al., 2015). Research using CO_2 emissions as a proxy for environmental health has identified a relationship between a country's economic development and environmental deterioration (Raupach et al., 2007). Despite the growing body of research in this area, the relationship between economic growth and environmental degradation, driven by CO_2 emissions from economic activities, remains complex (Chaudhury et al., 2023). This complexity arises because each study has employed different methodologies and approaches in its investigation of this phenomenon. Oman is situated on the southeast Arabian Peninsula and features diverse landscapes, from mountains to deserts to mangroves. Its ecosystems offer opportunities for effective environmental management. The economy is mainly based on crude oil exports, with a push towards diversification under Vision 2040, which focuses on sustainability and food security. Oman imports over half of its food to meet the needs of its growing population, and climate change is expected to put further pressure on agriculture and food imports.

Climate change threatens Oman's economic growth by causing issues such as rising temperatures, groundwater pollution, and increased water salinity, especially since Oman relies on desalination for its freshwater (Amoatey et al., 2022). Various social and institutional challenges further impact the country's response to climate change (Alrawahi et al., 2023). Forecasts indicate Oman may experience a temperature rise of +4°C by 2100, decreased rainfall, and higher drought indices (Alrawahi et al., 2023). Food security, economic development, and climate change affect Oman's vulnerability in the 21st century (Saboori et al., 2022). The government has restructured its Ministry of Environment and Climate Affairs into an Environment Authority to handle climate-related policies and strategies (Amoatey et al., 2022). Oman's economy mainly depends on the energy sector, with tourism providing additional revenue. The increasing global energy demand fuels climate change, while local challenges include fluctuations in energy supply and demand (Kilinc-Ata, 2025). Oman is prone to natural disasters such as floods, cyclones, sandstorms, and droughts, particularly cyclones, which account for the majority of natural hazards (Mohammed and Abdel-Gadir, 2023). Increasing vulnerabilities include rising sea levels, groundwater over-extraction, salinity issues in agriculture, and intensified droughts. Future rainfall patterns are likely to change, causing brief but severe flash floods, while sandstorms are expected to occur more frequently, affecting areas such as Muscat (Al-Badi et al., 2022).

Even though the Environment Authority has been restructured and there is a clear focus on sustainability, Oman's carbon emissions are still closely linked to its industrial activity. The main issue is that it is unclear where Oman stands on the environmental Kuznets curve (EKC). If the country is still on the rising part of the curve, ongoing economic growth without major policy changes could cause lasting environmental harm. This would put food security and water stability at risk, which are central to Vision 2040.

Numerous studies have examined the effects of economic growth on the environment (Dinda, 2004; Apergis and Ozturk, 2015). Many researchers employ methodologies to demonstrate the relationship between economic growth and environmental outcomes over both short- and long-term horizons, often using the environmental Kuznets curve (EKC) framework (Agras and Chapman, 1999; Al-Mulali et al., 2015). The EKC posits an inverted U-shaped relationship between economic growth and environmental degradation: as economic growth increases, environmental degradation initially rises, then falls. At a certain inflection point, however, this relationship reverses, resulting in reduced environmental harm despite continued economic growth (Leal and Marques, 2022). This framework is applied to both developed and developing nations to analyze the relationship between economic development and environmental quality. In developed countries, pollution levels have declined after surpassing their peak economic expansion. In contrast, many developing nations remain in the initial phase of the curve, where economic growth is associated with worsening environmental conditions (Naveed et al., 2022).

The environmental Kuznets curve (EKC) hypothesis is a foundational concept in environmental economics that describes the relationship between economic development and environmental degradation (Ahmad et al., 2021). EKC analyses across various economic systems have produced divergent results due to factors such as industrialization, technological advancement, and policy implementation (Dinda, 2004). Developed economies, including the United States and European Union member states, typically exhibit declining pollution levels after reaching the EKC inflection point, whereas developing economies must balance economic growth with environmental protection (Mahmood et al., 2022). The EKC trajectory is shaped by three primary contextual determinants: resource availability, institutional structures, and socio-economic objectives. Oman, a country heavily reliant on petroleum exports, is particularly influenced by EKC projections. Oman's economy, with its emphasis on energy production, presents distinctive conditions for examining sustainability challenges in relation to economic development objectives outlined in Vision 2040 (Wang et al., 2024).

The imperative for environmental protection in Oman is heightened by its arid climate, its significant reliance on desalination for freshwater, and its vulnerability to the adverse effects of climate change (Wang et al., 2023). The increasing frequency of severe weather events, such as cyclones and droughts, underscores the necessity for robust, sustainable environmental policies. This research situates Oman within the EKC discourse, thereby contributing to the empirical literature on the Gulf region and highlighting both sustainability challenges and opportunities in resource economics (Ajanaku and Collins, 2021). The findings offer policymakers critical insights for developing economic policies that integrate environmental stewardship in accordance with current climate change agreements and the United Nations Sustainable Development Goals framework (Shah et al., 2022).

This study critically evaluates the relationship between economic expansion and environmental contamination in Oman from 1998 to 2022, utilizing the Environmental Kuznets curve (EKC) framework. This analysis is essential given the significant carbon dioxide emissions and escalating environmental health concerns nationwide. The research identifies the current stage of the EKC in Oman's economy and compares environmental conditions between Oman and other gulf cooperation council (GCC) countries. Strategic initiatives should prioritize strengthening oversight of environmental policy to achieve sustainable development, reflecting Oman's commitment to addressing environmental challenges both domestically and regionally.

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

The environmental Kuznets curve (EKC) has become a central concept in environmental economics for explaining the complex relationship between economic growth and environmental degradation. According to Ridwan et al. (2024), the EKC suggests that increases in per capita income initially led to higher levels of environmental pollution, but pollution declines once a threshold income level is reached. The curve, initially proposed by Murshed et al. (2021), has informed the development of this hypothesis. The EKC framework underpins extensive research on the environmental impacts of economic activities, particularly in the contexts of industrialization and urbanization (Dinda, 2004).

Empirical studies report inconsistent findings regarding the existence of the environmental Kuznets curve (EKC) hypothesis, with outcomes varying according to pollution type, country development stage, and analytical methodology. The foundational concepts of the EKC hypothesis were articulated in investigations by Kaya Kanlı and Küçükefe (2023), which demonstrated that pollutants such as sulfur dioxide (SO_2) and suspended particulate matter (SPM) exhibit an inverted U-shaped relationship with income levels. The global environment monitoring system provided air and water quality analyses for urban and river conditions across multiple countries. Research by Hao et al. (2022) identified pollution reduction thresholds below US$ 8,000, with regional differences in pollutant-specific reduction levels (Mahmood et al., 2023). Sun et al. (2024) corroborated these results, further establishing that shifts in economic structure from agriculture to industry and subsequently to services drive transformations in pollution levels.

The EKC hypothesis is conceptualized through the combined analysis of scale, composition, and technique effects (Hashmi et al., 2022). In the early stages of economic development, scale effects predominate, as increased production and consumption drive higher resource use and pollution. The transition from a traditional to an industrial economy introduces composition effects, resulting in significant environmental degradation within specific industrial sectors. As income levels rise, technique effects become more influential, driven by technological innovation, stricter environmental regulations, and the adoption of cleaner production methods (Acaroğlu et al., 2023). Higher income levels also heighten public concern for environmental quality and ecological well-being, as individuals gain the capacity to prioritize these issues over basic survival needs (Liu et al., 2023).

The EKC hypothesis is widely used, but many researchers question whether it applies in all situations and how it affects policy decisions. Some critics doubt that the inverted U-shape relationship between pollution and economic growth holds true for every pollutant and environment. For example, evidence for the EKC with CO_2 and other global pollutants remains unclear (Sun et al., 2024), whereas the hypothesis is more robust for local pollutants such as SO_2 and SPM. In developing countries, CO_2 emissions tend to rise steadily with income because energy use and fossil fuel consumption are major factors (Taghvaee et al., 2022). The EKC framework has limitations when addressing global problems like climate change, as international cooperation is more important than relying solely on income-based pollution reduction measures (Ma et al., 2024). The hypothesis is also challenged because it assumes that economic growth alone will fix environmental issues. Investing higher income in cleaner technology and environmental protection depends on strong institutions, good policies, and supportive social values (Agozie et al., 2022). Without proper environmental regulations, economic growth can worsen pollution, especially in countries where industry relies on extracting natural resources (Ma et al., 2024). This is a larger problem in developing countries, where weak governance and limited funding often prevent the implementation of sustainable practices (Liu et al., 2023).

Researchers have improved EKC modeling by adding more variables and studying different nonlinear patterns. Ongan et al. (2021) used a cubic model to identify potential turning points in the relationship between income and environmental damage. Their study shows that the short-term inverted U-shaped relationship persists, but in wealthier societies, pollution patterns become more complex, with multiple turning points or even rising pollution. Setyari and Kusuma (2021) found that renewable energy use and urbanization are key factors shaping the EKC relationship, and they highlight the need for unified approaches to achieve sustainable development. The gulf cooperation council (GCC) countries have unique economic and environmental conditions, making them important for testing the EKC hypothesis. These countries face challenges because they rely on hydrocarbon exports while trying to protect the environment (Filippidis et al., 2021). Some GCC countries show EKC patterns for certain pollutants (Murshed et al., 2021), but the overall trend is unclear due to the dominance of the energy sector and limited economic diversification. Oman is a good case for studying the EKC hypothesis because it depends on oil exports, is vulnerable to climate change, and is currently undergoing economic changes as part of Vision 2040 (Agozie et al., 2022).

3. METHODOLOGY

3.1. Data Sources

Annual time-series data for the Sultanate of Oman from 1998 to 2022 were utilized. The analysis focuses on CO_2 emissions per capita (metric tons) as the dependent variable and real GDP per capita (constant US dollars) as the independent variable. Data sources include the World Bank's world development indicators (WDI) and the national centre for statistics and information (NCSI) of Oman to ensure data accuracy.

To address the significant volatility in the variance of the data, both variables were transformed into their natural logarithmic forms, ($LnCO_2$ and LnY (logarithm of CO_2 emissions and logarithm of GDP per capita). This logarithmic transformation is a common practice in econometric analyses, as it helps stabilize the variance and smooth the data, making it more suitable for regression modeling (Vergara et al., 2023; Mougenot et al., 2022). All statistical analyses were conducted using E-Views software, version 13, which is widely recognized for its robustness in handling time series data.

3.2. Descriptive Statistics and Preliminary Analysis

This research used descriptive statistics to evaluate the study variables. The first data review showed patterns in the mean values, data spread, and overall organization. Descriptive statistics were calculated for both the original and transformed data to fully understand the dataset, especially after applying logarithmic changes. This transformation reduces heteroscedasticity and helps researchers interpret elasticity coefficients in regression analysis. The method follows environmental economics standards, as logarithmic transformations are a common way to address non-linear patterns and improve predictive models.

3.3. Unit Root Tests

The validity of time-series regression depends fundamentally on the stationarity of the underlying data. Estimating a model with non-stationary variables often leads to spurious regression, in which high R^2 values and significant t-statistics are misleading and render the empirical findings statistically invalid.

To ensure the reliability of the results, this study employed two complementary unit root tests: the augmented dickey-fuller (ADF) test and the Phillips-Perron (PP) test. The ADF test addresses potential autocorrelation by incorporating lagged difference terms of the dependent variable. In contrast, the PP test utilizes a non-parametric approach to control for serial correlation and heteroscedasticity without requiring the specification of a lag length.

Both tests were evaluated at the 5% significance level to determine the integration order. As shown in Table 1, the results indicate that both variables ($LnCO_2$ and LnGDP) are non-stationary at their levels, indicating a unit root. However, upon applying first-order differencing, the null hypothesis of a unit root was rejected. This confirms that the series are integrated of order one (I[1]), which is a prerequisite for proceeding with the vector autoregressive (VAR) and Granger causality frameworks.

3.4. Model Specification

Building on the theoretical framework of the environmental Kuznets curve (EKC), this study estimates two econometric models to examine the relationship between economic growth and environmental degradation in Oman. The first model is the traditional EKC specification, which posits a quadratic relationship between GDP per capita and CO_2 emissions. The second model extends this framework by incorporating a cubic term to capture potential non-linearities and turning points in the relationship. The models are specified as follows: Original EKC model (quadratic specification):

$$lnCO2t = \beta 0 + \beta 1lnyt + \beta 2\ (lnyt)2 + \mu t \quad (1)$$

Cubic EKC model (extended specification):

$$lnCO2t = \beta 0 + \beta 1lnyt + \beta 2\ (lnyt)2 + \beta 3\ (lnyt)3 + \mu t \quad (2)$$

3.5. Vector Autoregressive (VAR) Model

The study utilizes the vector autoregressive (VAR) model to study the dynamic linkage between CO_2 emissions and economic growth. The VAR framework provides ideal conditions for tracking multiple time series relationships because it analyzes all variables as endogenous and enables Granger causality analysis. The proper lag period for VAR modeling is resolved by applying the Akaike information criterion (AIC) and Schwarz Bayesian criterion (SBC) measurement methods. Two lags provide the optimal results in forecasting the original EKC model and the cubic EKC model. The VAR framework enables researchers to establish causal relationships by implementing the Granger Causality test because the framework allows researchers to predict future outcomes based on past values.

Table 1: Dickey-fuller and phillips-perron tests

Variable	Level I (0)		First difference I (1)	
	ADF test	PP test	ADF test	PP test
CO_2	−1.31	−0.60	−5.63***	−8.49**
Y	−2.29	−1.54	−2.88*	−2.76*

***, *, and * significance at the 1%, 5%, and 10% levels, respectively

3.6. Validation of the EKC Hypothesis

The validity testing of environmental Kuznets curve (EKC) hypothesis requires specific patterns to emerge in the models that connect economic growth to environmental degradation. A positive GDP per capita coefficient together with a negative GDP per capita squared coefficient in the quadratic specification will confirm the EKC hypothesis. The relationship shows a flipped U-shaped path which demonstrates that environmental degradation grows as GDP increases until it reaches a point where the degradation levels start to decrease. The cubic specification verifies an inverted U-shaped curve presence with possible turning points when GDP per capita has a positive coefficient alongside negative GDP per capita squared coefficient and a zero GDP per capita cubed coefficient. Multiple turning points during time may exist in the relationship when the coefficient for GDP per capita cubed does not equal zero. The patterns obtained during analysis help identify Oman's position on the EKC stage and guide policy decisions regarding economic development and environmental conservation.

3.7. Robustness Checks

Multiple diagnostic tests are performed to verify the research solidity in this study through examinations of autocorrelation and heteroscedasticity and stability model tests. The estimated model residuals undergo analysis to check whether they satisfy the requirements of independent behavior and normal distribution. The validity of regression results depends on these diagnostic tests which demonstrate both result validity and analysis generalizability and reliability.

4. RESULTS AND DISCUSSION

Table 1 summarizes the results of the stationarity tests. For both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests, the null hypothesis of a unit root could not be rejected at the level for $LnCO_2$ and LnY because the test statistics exceeded the critical values at the 5% significance level. After first differencing, the P-values for both variables fell below the 0.05 threshold, and for CO_2, below 0.01. This result indicates that the series becomes stationary, confirming that the variables are integrated of order one, I(1).

The analysis used both the Dickey-Fuller and Phillips-Perron tests to examine the variables $lnCO_2$ t and Lnyt. In all test setups, whether including an intercept, an intercept and trend, or neither, the P-values were above 0.05, showing that the series are non-stationary. To address this, first differences were calculated to find a stationary series. After differencing, all P-values dropped below 0.05, so the null hypothesis of a unit root was rejected, confirming that the differenced series are stationary. This process produced the variables $dlnCO_2$ and Lyt. Following the approach in previous studies, the analysis continued with the transformed variables in natural logarithms. Next, two vector autoregressive (VAR) models were estimated to determine which best fit the research goals and explain the EKC in Oman. The first step was to select the optimal lag length using the Akaike information criterion (AIC) to choose the model with the lowest value.

4.1. Original Model Based on the EKC

The lag selection criteria shown in Table 2 confirm that Lag 2 is the optimal choice, as indicated by the majority of the indicators (LR, FPE, AIC, and HQ). The high R^2 values suggest that the model explains a significant portion of the variance in Oman's CO_2 emissions.

The original model results shown in Table 3 indicated a strong support Oman's current direction in environmental development. To test the EKC hypothesis, we examine how LY (Income) and LY^2 (income squared) relate in the CO_2 equation.

The VAR estimation results for the LCO_2 equation indicate a high goodness-of-fit ($R^2 = 0.95$), suggesting that income levels are the principal determinants of environmental degradation in Oman. The significant F-statistic (213.62) further substantiates the robustness of the income-emission relationship. The model parameters correspond to the "scale effect" phase of the Environmental Kuznets Curve (EKC), in which increased economic activity, especially within energy-intensive sectors, leads to higher carbon emissions. Although the quadratic model remains robust, the comparative evaluation of information criteria (AIC and SC) suggests the potential value of investigating a cubic specification to gain deeper insights into Oman's long-term sustainability trajectory.

Table 4 presents the Granger causality results, demonstrating a dynamic relationship between economic growth and environmental quality in Oman. The analysis identifies a strong unidirectional causal relationship between economic growth and carbon emissions. In the ($LnCO_2$) equation, the joint significance of (Lny) and (Lny^2) produces a Chi-square statistic of 12.52 with a P = 0.0019, resulting in the rejection of the null hypothesis. These results confirm that historical economic growth significantly predicts current (CO_2) emission levels in Oman. Conversely, there is no evidence of a feedback loop between carbon emissions and economic growth. When (Lny) and (Lny^2) serve as dependent variables, the joint tests are statistically insignificant, with P-values above conventional significance levels. This finding suggests that changes in (CO_2) emissions do not Granger-cause variations in GDP per capita, indicating that environmental degradation has not historically preceded economic expansion in Oman.

These findings have significant policy implications for Oman's Vision 2040. The predominance of growth-driven emissions indicates that the scale effect is the main mechanism by which economic activity impacts the environment. Furthermore, the lack of reverse causality offers policymakers greater flexibility, suggesting that implementing stricter environmental regulations or shifting toward cleaner energy sources can proceed without an immediate threat to economic growth.

Table 2: VAR lag order selection criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	113.45	NA	1.35×10^{-08}	−9.60	−9.45	−9.56
1	163.94	83.41	3.71×10^{-10}	−13.21	−12.63*	−13.06
2	177.58	18.98*	2.60×10^{-10}*	−13.61*	−12.57	−13.37*

***, *, and * significance at the 1%, 5%, and 10% levels, respectively

Table 3: Estimate original model

Statistic	LCO_2	LY	LY^2
R^2	0.95	0.95	0.95
Adjusted R^2	0.95	0.95	0.95
Sum of squared residuals	0.28	0.06	136.72
S.E. of equation	0.12	0.05	2.61
F-statistic	213.62	202.18	201.91
Log likelihood	18.02	36.74	−53.13
Akaike AIC	−1.31	−2.93	4.88
Schwarz SC	−1.16	−2.79	5.03
Mean dependent variable	17.14	24.89	619.52
S.D. dependent variable	0.53	0.23	11.48

Source: Own elaboration, with E-views 13 software. SE: Standard errors, SD: Standard deviation

Table 4: Granger causality test for original model

Dependent variable	Excluded variable	Chi-square	df	Prob.
$LnCO_2$	Lny	8.19	1	0.00
	Lny^2	11.01	1	0.00
	All	12.52	2	0.00
Lny	$LnCO_2$	0.89	1	0.35
	Lny^2	1.82	1	0.18
	All	2.39	2	0.30
Lny^2	$LnCO_2$	0.87	1	0.35
	Lny	2.26	1	0.13
	All	2.41	2	0.30

The impulse response functions (IRFs) support the Granger-causality results by demonstrating the dynamic sensitivity of CO_2 emissions to economic fluctuations. Figure 1 shows that a one-standard-deviation shock to GDP per capita (LnY) has a positive, persistent effect on CO_2 levels over the 10-year period. The lack of a downward trend toward the zero axis within the forecast horizon suggests that Oman remains on the ascending segment of the Environmental Kuznets Curve (EKC). These findings highlight the predominance of the scale effect, in which economic growth is directly associated with increased environmental pressure, thereby emphasizing the need for proactive policy interventions to achieve decoupling.

4.2. Original Model Based on the EKC in Third Degree Polynomial Regression

Upon determining the optimal lag of 1 (as indicated in Table 5), the estimation of the VAR model was conducted. The R-squared values suggest that the four equations exhibit a significant degree of goodness of fit, as presented in Table 5. The third-degree polynomial regression provides a robust fit for the Omani economy. High R-squared values across the system equations

Figure 1: Impulse response functions for the quadratic environmental Kuznets curve model

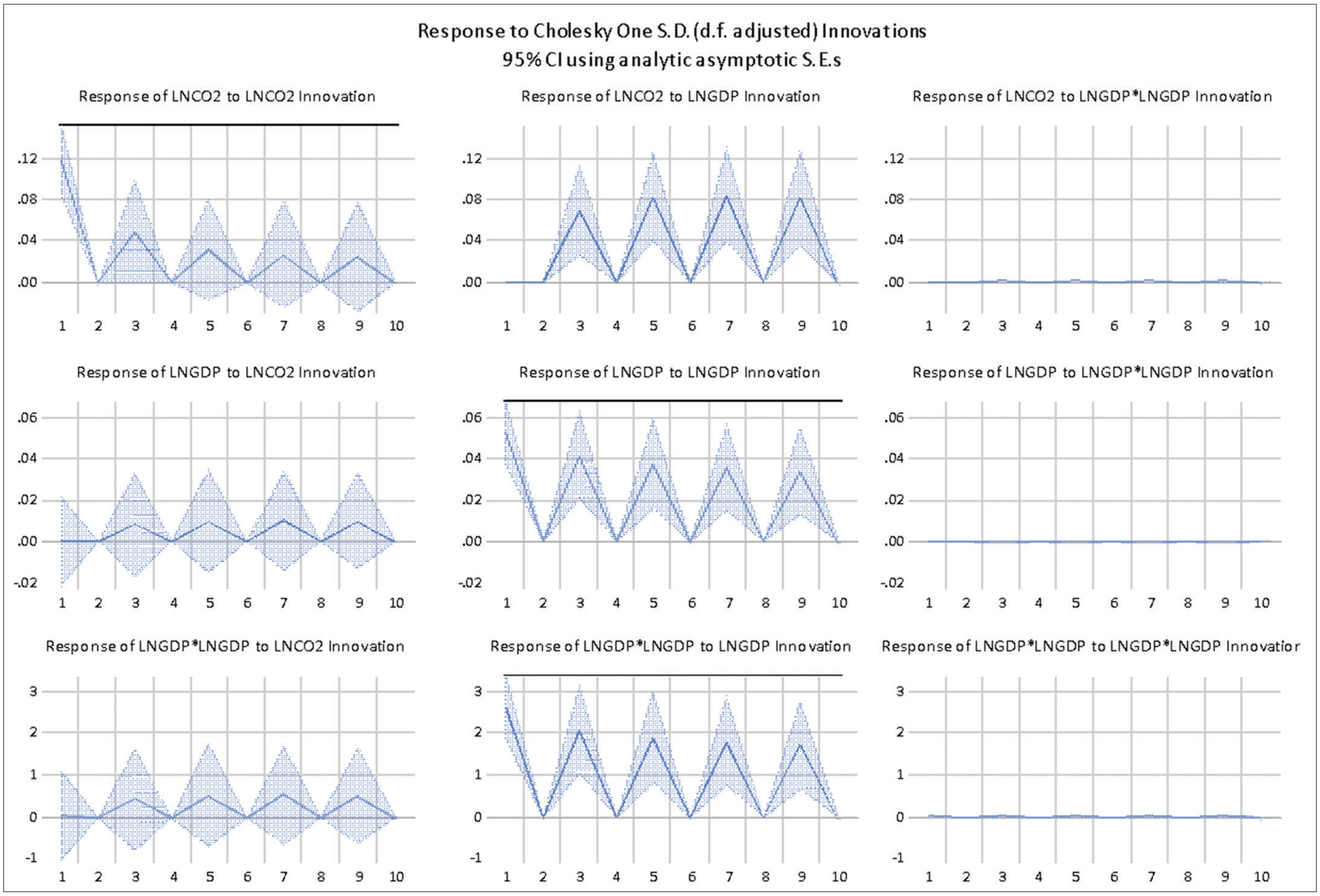


Table 5: VAR lag order selection criteria

Lag	Log likelihood (LogL)	Likelihood ratio (LR) test statistic	Final prediction error (FPE)	Akaike information criterion (AIC)	Schwarz information criterion (SC)	Hannan-Quinn information criterion (HQ)
1	324.99	Not applicable (NA)	7.81×10^{17}*	−25.74*	−24.90*	−25.51*

suggest that incorporating the cubic GDP term (LnY^3) effectively captures the non-linear dynamics of environmental degradation. This model is especially pertinent for Oman, as it assesses whether the nation faces the risk of a secondary increase in emissions, which is a common issue among high-income, energy-dependent states undergoing transitions within frameworks such as Vision 2040.

Table 6 shows the diagnostic results show that the cubic model for economic growth explains the data well. The (R^2) value of 0.96 for the ($LnCO_2$) equation means that income variables account for almost all changes in Oman's carbon emissions, which is a slight improvement over the quadratic model. The adjusted (R^2) is also high at 0.95, showing that adding the cubic term (Lny^3) makes the model better without making it too complicated.

Model stability and overall significance are further supported by the highly significant F-statistic of 138.73 and the low standard error of 0.12 for the emissions equation. These diagnostics suggest precise estimation and validate the relevance of the non-linear income specification in explaining environmental degradation. From a model-comparison perspective, the Akaike Information Criterion (−1.24) is comparable to that of the quadratic form, whereas broader system-efficiency measures point to the cubic model as a strong predictor. Within the EKC framework, this specification allows for a more nuanced interpretation of Oman's

Table 6: Autoregressive vector estimated with 1 lag for the original model in cubic regression

Statistic	$LnCO_2$	Lny	Lny^2	Lny^3
R-squared	0.96	0.97	0.97	0.97
Adjusted R-squared	0.95	0.96	0.96	0.96
Sum of squared residuals	0.27	0.04	99.80	138,319.30
S.E. of equation	0.12	0.05	2.29	85.32
F-statistic	138.73	176.72	177.53	178.30
Log likelihood	18.30	40.29	−49.51	−132.71
Akaike AIC	−1.24	−3.16	4.65	11.89
Schwarz SC	−1.05	−2.96	4.85	12.09
Mean dependent variable	17.14	24.89	619.52	15,421.98
S.D. dependent variable	0.53	0.23	11.48	428.13

SE: Standard errors, SD: Standard deviation emissions trajectory, including the possibility of an N-shaped relationship at higher income levels.

Table 7 shows the causality results from the cubic model support the findings of the quadratic model, but they also reveal greater complexity. Unidirectional causality to emissions In the $LnCO_2$ equation, each variable alone is not significant, but together, all income terms (Lny, Lny^2, Lny^3) have a joint $P = 0.0055$. This shows that economic growth as a whole Granger-causes CO_2 emissions in Oman. Income dynamics interestingly, for the income equations (Lny, Lny^2, Lny^3), emissions ($LnCO_2$) do not exert causality, with P-values consistently above 0.23. However, the growth terms strongly cause each other, which is expected in a polynomial framework. Policy implication: The results suggest that Oman's carbon footprint is heavily determined by its growth trajectory, but the environment does not yet constrain economic performance.

Table 7: VAR granger causality/block exogeneity wald tests

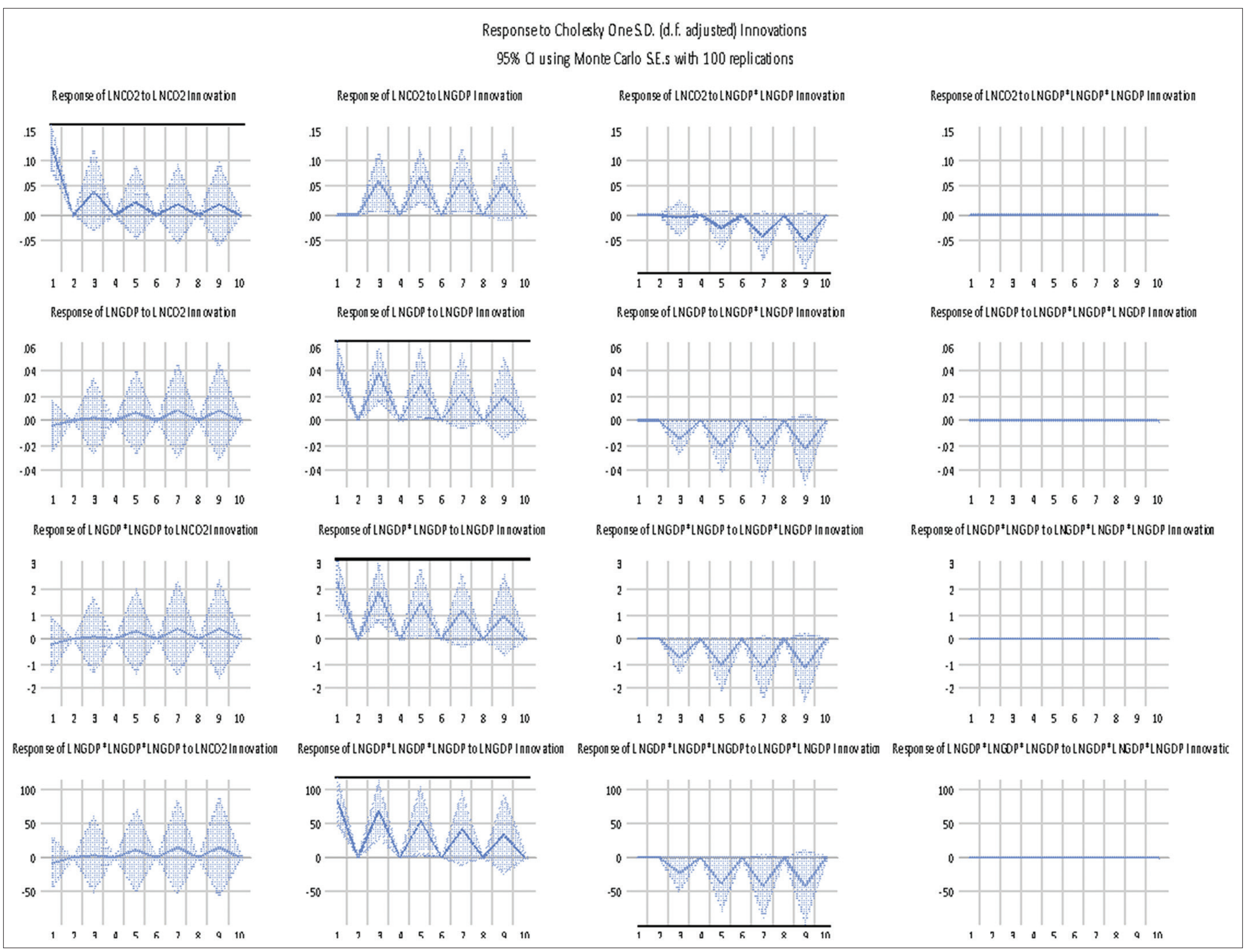
Dependent variable	Excluded variable	Chi-square	Df	Prob.
$LnCO_2$	Lny	0.50	1	0.48
	Lny^2	0.50	1	0.48
	Lny^3	0.46	1	0.50
	All (growth terms)	12.64	3	0.01*
Lny	$LnCO_2$	1.38	1	0.24
	Lny^2	6.82	1	0.01
	Lny^3	6.88	1	0.01
	All	9.98	3	0.02*

Figure 2 illustrate a positive, persistent response of carbon emissions to shocks in GDP per capita and its polynomial terms. The lack of a clear downward trend toward negative values within the 10-period window confirms that the Omani economy is positioned before the EKC turning point. This reinforces the necessity for the proactive transition strategies highlighted in Oman's Vision 2040 to decouple industrial expansion from environmental degradation.

5. DISCUSSION

This study provides useful insights into the link between economic growth and environmental decline in Oman by examining evidence from the EKC hypothesis. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests show that the $LnCO_2$ and Lny variables are not stationary at their original levels, but become

Figure 2: Impulse response functions for the cubic environmental Kuznets curve model



stationary after first differencing. Previous research recommends making time series data stationary to avoid misleading regression results. As seen in other EKC studies on developing economies (Mougenot et al., 2022), first-differencing the variables confirms their I (1) status according to the test results. The original EKC model, which used a quadratic approach, showed strong correlations as all three equations had high R-squared values. This suggests the model effectively explains the link between economic growth and CO_2 emissions in Oman.

The Granger causality test found that both Lny and Lny^2 have a causal effect on $LnCO_2$, with P-values below 0.05. However, there was no evidence of reverse causality, since the P-values for Lny and Lny2 were above the significance threshold. According to Pradhan et al. (2021), economic development first causes environmental decline before pollution-control measures become effective. In Oman, economic growth has not yet led to major changes in emission-reduction policies or pollution technologies, as there is no Granger causality from $LnCO_2$ to Lny or Lny^2.

The cubic EKC model revealed more about the complex, non-linear relationship between income and environmental decline by using third-degree polynomial terms. This model had higher R-squared values than the quadratic model, showing a better fit. The Granger causality analysis found that $LnCO_2$ responds significantly to the income variables Lny, Lny^2, and Lny^3, as indicated by P-values below 0.05. The link between income growth and environmental harm becomes more complex, with several turning points. Vergara et al. (2023) support these findings, noting that the traditional inverted U-shaped EKC does not capture long-term environmental trends in resource-dependent economies like Oman.

Impulse analysis shows that Oman is still on the upward part of the Environmental Kuznets Curve, before the stage where pollution starts to decrease. The response curves for $LnCO_2$ and Lny, along with Lny^2 and Lny^3, show steady growth over a 10-period analysis in both the quadratic and cubic models. This means the Omani economy has not yet reached its turning point. Murshed et al. (2021) also finds that many gulf cooperation council (GCC) countries, including Oman, have not reached the EKC turning point, as economic growth continues to worsen environmental damage. Oman and its leaders need to prioritize policy measures to address the environmental impacts of economic growth, since the impulse response analysis shows no turning point yet.

These findings add to the research on the Environmental Kuznets Curve in developing and resource-based economies. This study supports earlier work showing that economic growth first leads to environmental decline, but highlights unique challenges for Oman due to its oil-based economy and vulnerable natural areas. The impulse response analysis shows there is no turning point yet, which means progress toward sustainable development is blocked by these factors. Ma et al. (2024) agree, stressing that integrated environmental policies are important for Oman to manage economic diversification and protect against climate change.

6. CONCLUSION, LIMITATIONS AND FUTURE STUDIES

The research investigated whether the Environmental Kuznets Curve hypothesis was accurate in Oman by analyzing CO_2 emission relationships during the period from 1998 through 2022. The evaluation through advanced econometric techniques validated that Oman exists on the upward Kuznets curve because economic development and environmental destruction show a positive correlation pattern. According to research the EKC models fitted well but the cubic model succeeded in revealing subtle relationships between income levels and emissions. Conducted tests demonstrate that CO_2 emissions respond to economic growth but not vice versa and the impulse response analysis shows Oman is still behind the stage when environmental degradation decreases. The findings correspond to the work of previous research on economies in development, which suggests that progress with economic development is accompanied by difficulties in carrying out environmental sustainability. Such results serve as a testament to why proactive policy measures are vital for Oman, its very agriculture kingdom, to emerge from its reliance on hydrocarbon exports to a sustainable development. To reduce emission and promote an environmental culture, there’s a need for investments in renewable energy and stricter environmental regulations as well as public awareness campaigns. With its implementation of these strategies within its Vision 2040 framework, Oman could come closer to achieving the EKC’s turning point, at which economic growth is separated from environmental harm. This study adds to increasingly vast literature on the EKC hypothesis, especially in terms of resource dependent economies. It advises the policymakers and stakeholders the need to balance between economic growth and environmental sustainability to achieve sustainable long-term prosperity and ecological resilience.

Oman is currently situated on the ascending limb of the Environmental Kuznets Curve, where economic growth and CO_2 emissions remain positively correlated. This unidirectional causality from GDP to emissions highlights a dominant scale effect, indicating that the nation has not yet reached the environmental turning point. To align with Vision 2040, Oman must transition toward a technique that integrates renewable energy and stricter environmental regulations to decouple growth from degradation. Future research should expand on these findings by incorporating broader ecological indicators and comparative regional analyses.

This research offers significant practical implications for policymakers and stakeholders in Oman, particularly those engaged with Vision 2040 and the Sustainable Development Goals. Oman is currently exhibiting an upward trend along the environmental Kuznets curve (EKC), in which economic growth is associated with rising CO_2 emissions, underscoring the urgent need for environmental protection measures. Policymakers should allocate resources to renewable energy technologies, such as wind and solar power, as these options reduce fossil fuel consumption and lower carbon emissions. Achieving sustainability objectives requires robust environmental regulations and effective enforcement mechanisms to ensure industrial practices remain aligned with sustainability targets.

Environmental awareness campaigns can educate both consumers and businesses about eco-friendly practices, thereby fostering a culture of environmental responsibility. Integrating these measures into national development strategies will accelerate Oman's progress toward the EKC decoupling point, enabling economic growth without detrimental environmental impacts. Sustained commitment to these initiatives will position Oman as a resilient and sustainable nation, capable of addressing global climate change challenges and securing long-term national sustainability.

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