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Unveiling the Environmental-Economic Nexus: Cointegration and Causality Analysis of Air Pollution and Growth in Oman

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Abstract: This article explores the intricate relationship between environmental degradation, specifically air pollution, and economic growth in the Sultanate of Oman spanning the period from 1990 to 2022. We employ cointegration and vector error correction models to uncover both short- and long-term dynamics in the association between air pollution and economic growth. Furthermore, Granger causality analysis is utilized to investigate the causal links between these crucial variables. This data encompasses factors related to environmental quality and various control variables. The empirical results unveil a sustained long-term cointegration connection between the variables. Additionally, our findings highlight a statistically significant positive impact of economic growth and energy consumption on CO_2 emissions. Furthermore, the short-term analysis reveals an annual adjustment of approximately 14.1% in N_2O emissions disequilibrium. The Granger causality study indicates unidirectional causal relationships involving N_2O emissions, economic growth, and CO_2 emissions. The implications of these findings for Oman's policy landscape are substantial. To effectively reduce greenhouse gas emissions, it is imperative for Oman to establish robust climate change policies. Additionally, the government can play a pivotal role in encouraging and endorsing the use of renewable energy sources, such as green hydrogen, as a promising alternative to traditional oil and gas resources.

Keywords: air pollution; cointegration; oman

1. Introduction

The interplay between air pollution, climate change, and economic growth has garnered significant attention from scholars and policymakers in recent times. It is noteworthy that many sources of "conventional" air pollution are also primary contributors to CO2 and other greenhouse gases (GHGs), which play a pivotal role in global warming [2]. Climate change remains an ongoing global concern due to its profound and far-reaching impacts on human existence on Earth. The rapid expansion of economic activities, urbanization, and population growth has resulted in an unprecedented surge in the demand for energy consumption. These factors collectively contribute to the escalating levels of greenhouse gas emissions and environmental degradation. Consequently, one of the paramount developmental challenges facing the world today revolves around achieving sustainable economic growth rates while delicately balancing this expansion with environmental preservation. Numerous studies have examined CO_2 emissions and air pollution in the Gulf Cooperation Council (GCC) nations. Research indicates positive correlations among urbanization, energy utilization, and CO_2 emissions in GCC countries [3]. Furthermore, it has been observed that various climatic elements, including wind speed, wind direction, temperature, relative humidity, and rainfall, significantly influence the levels of CO_2 and hydrocarbons in the atmosphere [4]. These studies collectively shed light on the intricate relationships among urbanization, energy consumption, GDP growth, foreign direct investment, financial development, and climatic factors in the GCC nations [5]. In the pursuit of evaluating and devising solutions to achieve a zero-carbon neutrality target by 2050, numerous Conferences of Parties (COPs) have been convened to address the pressing issue of climate change. Aligned with the objective of limiting global warming to 1.5°C,

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as outlined in the Paris Agreement, Oman has made a commitment to attaining net-zero emissions by 2050. Oman's concerted efforts in this endeavor encompass a strong focus on transitioning to clean energy sources and bolstering resilience. Initiatives such as the National Strategy for Adaptation and Mitigation to Climate Change and the second nationally determined contribution (NDC) underscore the imperative need for energy infrastructure resilience against climate change impacts. Furthermore, Oman Vision 2040 and the National Energy Strategy set ambitious goals for expanding renewable energy and enhancing energy efficiency. This paper's primary objective is to explore the evolving relationship between air pollution and economic growth in Oman over the period spanning 1990 to 2022, thereby contributing new insights into this critical association. Furthermore, an analysis of the interplay among economic growth, air pollution, and other relevant control variables holds the potential to offer valuable perspectives on this issue. Notably, prior research has not directly scrutinized the interconnectedness of air pollution, climate change, and economic growth in the context of Oman, adding to the impetus for this study. Our secondary methodological contribution lies in the utilization of various econometric techniques, including cointegration tests to assess the long-term dynamics of the variables and dynamic ordinary least squares (DOLS). Additionally, we employ panel Granger causality to elucidate the direction of causality between these variables. The subsequent sections of this article are structured as follows: In Section 2, we provide a concise review of the existing literature. Section 3 outlines the methodology, including variable definitions and data sources. Section 4 presents the empirical findings. The concluding section is reserved for summarizing the outcomes and offering policy recommendations.

1.1. Greenhouse Gas Emissions in Oman

In Oman, greenhouse gas emissions are primarily caused by both natural and human factors. Although Oman's emissions are relatively low compared to some industrialized countries, they still contribute to global climate change. The primary causes of greenhouse gas emissions in Oman include:

1. Energy Production: The energy sector is a significant contributor to greenhouse gas emissions in Oman. The country heavily relies on oil and natural gas to generate electricity and fuel its industry, which results in the combustion of fossil fuels in power plants and industrial processes, releasing significant amounts of carbon dioxide (CO_2) into the atmosphere.
2. Transportation: Oman's growing economy and population have led to an increase in the number of vehicles on the road, resulting in gasoline- and diesel-powered vehicles being the major sources of CO_2 emissions. The lack of a well-developed public transportation system also contributes to the reliance on private vehicles.
3. Industrial Processes: Industrial activities, such as petrochemical production, cement manufacturing, and metal smelting, release greenhouse gases as byproducts of their operation. These emissions include CO_2 and other gases like methane (CH_4) and nitrous oxide (N_2O).
4. Waste management plays a crucial role in reducing methane emissions. The improper disposal of solid waste in landfills can result in anaerobic decomposition of organic materials, leading to the generation of methane. Conversely, adopting appropriate waste management and recycling practices can help to minimize these emissions.
5. Agriculture is a significant contributor to greenhouse gas emissions in Oman, particularly from methane emissions resulting from enteric fermentation in livestock and rice cultivation. Nitrous oxide emissions can also arise from the application of synthetic fertilizers in agriculture.
6. Land use changes, such as deforestation and urbanization, can lead to a decline in carbon sinks and the release of stored carbon into vegetation and soils. This reduction in carbon sinks can have a significant impact on the environment and climate.
7. Wastewater management systems can contribute to greenhouse gas emissions if not properly managed. Improved wastewater management systems can help to reduce methane emissions and improve overall environmental health.
8. Natural factors, such as wildfires, dust storms, and geological emissions, can also release greenhouse gases into the atmosphere. However, these events are exacerbated by climate change

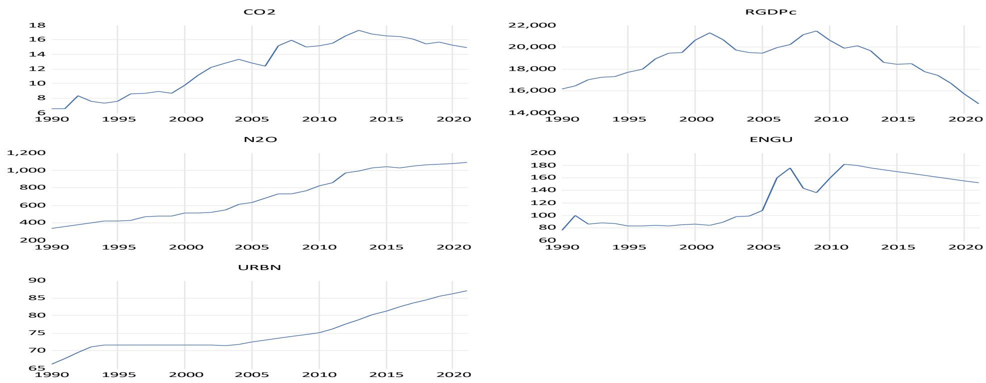

Figure 2. Trend in CO_2, N_2O, Urbanization, Energy use and GDP per-capita growth.

1.2. Causes of Air Pollution in Oman

Air pollution in Oman can be attributed to a variety of factors , many of which are common to urban areas and industrialized regions around the world. Some of the primary causes of air pollution in Oman include:

1. Industrial Emissions: Industrial activities, including oil and gas extraction, petrochemical manufacturing, and other heavy industries, release various pollutants into the air. These emissions can include sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter, and volatile organic compounds (VOCs).
2. Vehicle Emissions: The increasing number of vehicles on the road contributes to air pollution. Diesel and gasoline vehicles emit pollutants such as carbon monoxide (CO2), NOx, VOCs, and particulate matter.
3. Construction and Infrastructure Development: Rapid urbanization and construction projects can lead to dust and particulate matter in the air. These particles can cause respiratory problems and reduce air quality.
4. Natural Sources: Dust storms, especially in the arid climate of Oman, can contribute significantly to air pollution. Dust and sand particles are lifted into the air and can affect air quality when they settle.
5. Maritime Transport: Oman's strategic location near the Arabian Sea and the Gulf of Oman means it has a significant shipping industry. Ship emissions can include sulfur dioxide, NOx, and particulate matter, affecting coastal air quality.
6. Waste Management: Inefficient waste disposal and open burning of trash can release pollutants into the air. This is especially a concern in some less-developed areas.
7. Oil and Gas Operations: Oman is a major oil and gas producer, and the extraction and processing of these resources can release pollutants and greenhouse gases into the atmosphere.
8. Refineries and Petrochemical Plants: The processing of oil and natural gas in refineries and petrochemical plants can release various pollutants into the air.
9. Agricultural Activities: The use of fertilizers and pesticides in agriculture can release ammonia (NH3) and other chemicals into the atmosphere.
10. Power Generation: The combustion of fossil fuels for electricity generation can release pollutants into the air. Oman is working to diversify its energy sources, including through renewable energy projects, to reduce this source of pollution.

2. Related Literature

2.1. Economic Growth and Air Pollution

Several previous studies have investigated the link between economic growth and air pollution, with a focus on examining the long-term dynamics using the Environmental Kuznets Curve (EKC) theory. The EKC theory is founded on the concept of an inverted U-shaped relationship between a country's income level and its carbon emissions. Initially proposed by [6], the EKC hypothesis aims to explore the interplay between per capita income and environmental attributes. Their empirical investigations, however, introduced complexities to the Environmental Kuznets Curve (EKC) theory due to yielding a wide array of outcomes. The connection between economic growth and CO_2 emissions has also undergone extensive scrutiny in recent years, resulting in a mosaic of diverse and contradictory findings. For instance, studies conducted by [7–13] have identified a positive relationship between economic growth and carbon emissions. In contrast to the predictions of the EKC hypothesis, research by [14–17], has demonstrated that economic growth leads to a reduction in carbon emissions over the long term. Furthermore, [18] conducted an in-depth investigation into the interplay among N_2O emissions, economic growth, agricultural land utilization, and exports in Germany. They employed time series data and the Autoregressive Distributed Lag (ARDL) technique, covering the period from 1970 to 2012. Their results unveiled a curvilinear long-term association between N2O emissions and economic growth, thereby substantiating the presence of an Environmental Kuznets Curve (EKC) pattern within the context of Germany. By addressing the issue, which is a complex one with conflicting results, we can talk about how GDP growth affects air pollution. According to certain research, air pollution may rise as a result of economic expansion, especially if these expectations are high [19]. Other research, however, suggests that government initiatives can significantly improve the decoupling between economic expansion and air pollution [20]. Studies have shown that air pollution has a considerable detrimental impact on China's economic growth, further demonstrating the impact of air pollution on economic growth [21]. Additionally, elements including a nation's level of economic development, energy use, and industrial production affect the association between economic growth and air pollution [22,23], provide a summary of the MENA region's air pollution. They divided air contaminants into categories related to health and those related to climate change. They discovered that GHS is the primary pollutant posing a threat to people's health in the MENA region. In term of GCC, several articles have examined the relationship between air pollution and economic growth in the Gulf Cooperation Council (GCC) nations. According to studies, air pollution and economic growth are positively correlated in the GCC countries. [24,25] found that economic growth has a positive effect on CO_2 emissions and a negative effect on energy consumption. In return, energy consumption reduces CO_2 emissions [26]. [27]. According to the studies, urbanization and the use of clean energy can help in the long run to minimize pollutant emissions and achieve sustainable development [28]. Overall, the research shows that economic development and energy use are significant causes of air pollution in the GCC nations. In Oman, the connection between air pollution and economic growth is contingent upon a multitude of variables. Recent research, such as the study by [29], has revealed intriguing insights. Positive shocks to foreign direct investment inflows, economic growth, and capital investments have been associated with an increase in carbon dioxide emissions, both in the short and long terms. Conversely, it has been observed that adverse shocks to economic development and foreign direct investment inflows can lead to emissions reduction, as supported by [29]. The roles of foreign direct investments, economic growth, and capital investments in decarbonizing the economy of Oman. [29]

[30], findings provide compelling evidence for the presence of an Environmental Kuznets Curve in Oman. This theoretical framework posits that environmental quality may initially decline before ultimately improving as a country progresses economically, as elucidated by researchers such as [27,31]. In light of these findings and with the aim of reducing global carbon dioxide emissions, it is strongly recommended that Oman embraces green economic growth strategies. This approach

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involves curbing investments that have detrimental environmental consequences while simultaneously rejuvenating the financial sector, as proposed by [32].

2.2. Urbanization and Air Pollution

Urbanization has been found to have a significant impact on air pollution. Studies have shown that as the global population shifts from rural to urban areas, the marginal damage of air pollution emissions in urban areas increases, [33]. The effects of urbanization on air pollution vary across different income levels and countries. Demographic urbanization has a positive effect on PM2.5 concentrations, while spatial urbanization has a negative effect in high-income countries and a positive effect in other countries. Social urbanization presents the opposite trend, [34]. Urban form also plays a role in air pollution, with factors such as population density, aggregation index, and fractal dimension influencing PM2.5 and N2O concentrations. The impact of these factors varies based on city size, elevation, and road network density [35]. Additionally, urban development can alter urban meteorological characteristics and decrease the diffusion capability of pollutants, leading to increased pollutant concentrations [36]. Overall, urbanization and its various components have complex and heterogeneous effects on air pollution, highlighting the need for targeted measures to control pollution and improve air quality [37]. Oman's growing urbanization has contributed to an increase in air pollution. [38]. Local emission sources from transportation, industry, and energy production activities are present in Oman's major industrialized and urban centers, including Sohar, Muscat, Sur, and Salalah. [34. Poor air quality results from situations of stagnation and recirculation in these places, [39]. In addition, [40] discovered greater pollution levels in the urban residential region of Kuwait when comparing the air quality in the two locations: an industrial suburb in Oman, and an urban residential area. This means that Oman's metropolitan regions may likewise be facing high air pollution levels as a result of urbanization. According to [34], creating sustainable urbanization practices is essential for resolving the problems posed by urbanization-related pollution. Last but not least, numerous studies that examined how urbanization affects air quality discovered that it had a favorable indirect effect. Urbanization will rise when individuals relocate from rural to urban regions more frequently. Because of the increased energy use and carbon emissions, the quality of the air will decline. [41–52], and others have all studied this advantageous link.

2.3. Energy consumption and Air Pollution

Air pollution is significantly impacted by energy consumption. Numerous studies have demonstrated that increased energy use, especially the use of fossil fuels, results in higher pollution levels and detrimental health effects [53,54]. However, it has been discovered that using renewable energy sources helps to reduce air pollution [55]. Additionally, increasing air quality and reducing harmful impacts on health have been successful with the application of tight laws and clean energy policies [56]. Energy consumption has a significant effect on air pollution in Oman. [57]. The influx of energy-intensive industries without proper planning has led to air pollution becoming a serious public health concern in many developing countries, including Oman,[58]. It is crucial to decrease energy consumption in order to improve air quality, [59]. The use of renewable energy sources has been found to contribute to the reduction of air pollution, [60]. Therefore, it is important for the government to consider the relationship between energy consumption, economic development, and environmental protection when formulating energy and economic policies. By improving energy efficiency and finding a balance between energy, economy, and environmental protection, Oman can work towards solving its air pollution problems.

3. Model Specification and Data

The following models are used to examine how air pollution affects Oman's economic growth:

Model 1:

$$RGDPc_{it} = \alpha_0 + \alpha_1 CO_2 + \alpha_2 N_2O + \alpha_3 ENGU_{it} + \alpha_4 URP_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

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After taking the log model1 becomes:

$$\text{Ln RGDPc}_{it} = \alpha_0 + \alpha_1 \text{Ln } CO_2 + \alpha_2 \text{ Ln } N_2O + \alpha_3 \text{ Ln Ln ENGU}_{it} + \alpha_4 \text{ URP}_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots (2)$$

Where Economic growth denoted as RGDPc is a dependent variable. Independent variables include carbon dioxide emissions in metrics tons per capita (CO_2), Nitrogen dioxide (N_2O) "emitted from fossil consumption in kilotons", Energy use (kg of oil equivalent per capita) denoted by (ENGUit), and Percentage of urban population (% of total population denoted by (URPNit). The term εit is the error term bounded with the classical statistical properties

Model 2:

$$N_2O_{it} = \alpha_0 + \alpha 1 \text{ RGDPc}_{it} + \alpha_2 \text{ RGDPc}_{it}^2 + \alpha 3 \text{ ENGU}_{it} + \alpha_4 \text{ URP}_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

After taking the log for both sides model 2 becomes:

$$\text{Ln}N_2O = \alpha_0 + \alpha_1 \text{LnRGDP}c_{it} + \alpha_2 \text{LnRGDP}ci^2 + \alpha_3 \text{LnENGU}_{it} + \alpha_4 \text{LnURP}_{it} + \varepsilon_{it} \ldots\ldots\ldots (4)$$

Where Air Pollution (denoted by N_2O) is a dependent variable. Independent variables include Economic growth denoted by RGDPcit, Energy use (kg of oil equivalent per capita) denoted by ($ENGU_{it}$), and Percentage of urban population (% of total population denoted by (URP_{it}). The term ε_{it} is the error term bounded with the classical statistical properties

Table 1. Variables description and data sources.

Variable	Definition	**Codes of Variable**	**Source**
Dependent Variable	Real GDP at constant 2011 national prices (in mil. 2011US$)	RGDPc	PWT 10.0*
Independent Variables	CO2 emissions (metric tons per capita)	CO_2	WDI, 2022
	Nitrous oxide emissions (thousand metric tons of CO_2 equivalent)	N_2O	WDI, 2022
Control Variables	Urban population (% of the total population)	URBN	WDI, 2022
	Energy use (kg of oil equivalent per capita	ENGU	WDI, 2022

*Source: The information was taken from Penn World Table, 10.0. The description can be found in the reference: Feenstra, Robert C., Robert Inklaar, and Marcel P. Timmer (2015), "The Next Generation of the Penn World Table" American Economic Review, 105(10), 3150-3182, which is accessible for download at www.ggdc.net/pwt.

4. Results and Discussion

4.1. Descriptive Statistics

Table 1 below lists the descriptive statistics, minimum, maximum, mean, standard deviation (Std. Dev.), and coefficient of variation (CV) for each of these variables. The average ratio of the URBN throughout the years 1990 to 2022 was roughly 75.3%, with a coefficient of variation (CV) of 7.56. According to the CV score, the N_2O fluctuated the most

Table 1. Summary Statistics for the Model Variables.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	CV*
Ln RGDPc	18747.86	19189.55	21458.39	14792.32	1740.012	9.281123286
Ln CO_2	12.5148	13.0604	17.30974	6.566793	3.623088	28.95042669
Ln N_2O	703.4375	655	1090	340	265.1671	37.69590049
Ln URP	75.26406	72.6835	87.044	66.102	5.698879	7.571846377
Ln ENGU	126.1235	122.4913	181.8656	76.75578	39.29334	31.15465397

Table 2 presents the correlation matrix. The correlation demonstrates a strong connection between the RGDPC and all the other factors. RGDPC shows a strong negative correlation with URBN and N_2O.

Table 2. Correlation Matrix for the Model Variables.

Variables	RGDPC	CO2	N2O	URBN	ENGU
Ln RGDPC	1				
Ln CO_2	0.241857	1			
Ln N_2O	-0.096951	0.915519	1		
Ln URP	-0.316633	0.762638	0.94191	1	
Ln ENGU	0.056571	0.893628	0.89911	0.747322	1

4.2. DOLS estimates

To examine the association between RGDPc and climate change variables as well as other control variables, Model (1) is evaluated using the OLS estimation method. The DOLS results show that CO_2 and URBN have a positive and significant impact on RGDPc. The OLS results for N2O indicated a detrimental impact on growth. The unexpected finding comes from the energy variable, which indicates any appreciable impact on Oman's growth rate (Table 3)

Table 3. DOLS estimate model (1): Economic growth.

Dependent Variable: RGDPc

Sample: 1990 2021

Included observations: 32

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Ln CO_2	1164.263	145.1280	8.022319	0.0000
Ln N_2O	-21.55100	1.961402	-10.98754	0.0000
Ln URP	236.2125	11.94890	19.76856	0.0000

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Ln ENGU	12.30533	12.52318	0.982604	0.3342

R-squared	0.632001	Mean dependent var	18747.86
Adjusted R-squared	0.592572	S.D. dependent var	1740.012
S.E. of regression	1110.651	Akaike info criterion	16.97975
Sum squared resid	34539276	Schwarz criterion	17.16297
Log likelihood	-267.6760	Hannan-Quinn criter.	17.04048
Durbin-Watson stat	0.868178		

Model (2)'s primary objective was to determine whether Oman had an EKC between 1990 and 2022. The EKC hypothesis is tested via the estimate framework using economic and environmental indicators. The finding in Table 4 supports the EKC hypothesis, which is supported by the presence of a positive sign linked with economic growth and a negative sign connected with its quadratic term.

Table 4. DOLS estimate of model (2): Air Pollution.

Dependent Variable: N_2O

Sample: 1990 2021

Included observations: 32

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Ln RGDPC	0.149294	0.020395	7.320290	0.0000
Ln $RGDPC^2$	-3.81E-06	6.92E-07	-5.511561	0.0000
Ln CO_2	27.15082	5.716932	4.749195	0.0001
Ln URP	21.56324	2.447204	8.811379	0.0000
Ln ENGU	1.490693	0.361947	4.118538	0.0003

R-squared	0.986968	Mean dependent var	703.4375
S.E. of regression	32.43592	Akaike info criterion	9.939011
Sum squared resid	28406.40	Schwarz criterion	10.16803
Log-likelihood	-154.0242	Hannan-Quinn criter.	10.01492
Durbin-Watson stat	0.875121		

4.3. Unit Root Test

The outcomes of the model's series stationarity test are presented in Table 5. All series were found to be non-stationary at level according to the unit root (ADF) test, with a p-value greater than 0.05. Specifically, the variables are non-stationary in their level forms if the t-statistics for the ADF test of CO_2, N_2O, RGDPc, ENGU, and URP are not greater than the critical values at the 1%, 5%, and 10% levels, respectively. All variables were found to be stationary for the first difference with a p-value of less than 0.05, except for URBN and RGDPc which were integrated into order 1, I(1), and order 2, I(2), respectively.

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Table 5: Unit Root Test (ADF) for the Model Variables.

Variables	Level Critical Values					First Difference Critical Values				
	1%	5%	10%	t-values	p-values	1%	5%	10%	t-values	p-values
Ln CO_2	-3.662	-2.96	-2.612	-2.6192	0.4791	-3.670	-2.964	-2.621	-4.88688	0.0004*
Ln N_2O	-3.6617	-2.960	-2.6192	0.013780	0.9529	-3.6702	-2.9640	-2.612	-4.445660	0.0014*
Ln RGDPc	-3.6702	-2.9640	-2.621	-0.902244	0.7735	-3.6892	-2.9719	-2.6251	-6.875273	0.0000**
Ln URP	-3.6892	-2.9719	-2.6251	2.556510	1.0000	-3.6892	-2.972	-2.6251	-3.048164	0.0421**
Ln ENRU	-3.6892	-2.9719	-2.6251	-0.822161	0.7972	-3.679	-2.9678	-2.6229	-5.727279	0.0001*

The lag order selection criterion is shown in Table 6. All other criteria—including AIC, HQ, final prediction error (FPE), and sequential likelihood ratio (LR)—required three lags, with the exception of SC. Therefore, in our approach, lag three is considered to be the ideal lag.

Table 6. VAR Lag Order Selection Criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	23.02299	NA	6.60e-05	-1.112388	-0.980428	-1.066331
1	124.4002	180.2262	3.91e-07	-6.244458	-5.716618*	-6.060227
2	128.8578	7.181681	5.09e-07	-5.992102	-5.068382	-5.669699
3	145.3521	23.82506*	3.46e-07*	-6.408450*	-5.088851	-5.947875*

Note: * indicates lag order selected by the criterion; LR: sequential modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

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4.4. Cointegration test results

4.4.1. Results of Johansen Cointegration test

To determine if LnC02, LnN_2O, Ln RGDPc, Ln URP, and Ln ENGU are cointegrated, we conducted the Johansen multivariate Cointegration test. We first selected the optimal lag length using the minimum AIC and SC from the estimate of the unconstrained VAR model for the first differences of the aforementioned variables. We then found that the lag length is one. The Johansen Cointegration test was carried out since all variables are integrated in the same order, I (1) and I (2), and the results are presented in Table 7. The outcome revealed that there are three cointegration equations at the 5% significance level, and the trace value surpasses the critical threshold, while the maximum eigenvalue suggests there are only two cointegration equations.

Table 7. Johansen Cointegration Test: E-views 12 Output.

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.657911	84.88720	69.81889	0.0020
At most 1 *	0.512398	52.70670	47.85613	0.0163
At most 2 *	0.409125	31.15902	29.79707	0.0346
At most 3	0.255103	15.37452	15.49471	0.0521
At most 4 *	0.195855	6.539257	3.841466	0.0105

Trace test indicates 3 cointegrating eqn(s) at the 0.05 level

** Denotes rejection of the hypothesis at the 0.05 level*

***MacKinnon-Haug-Michelis (1999) p-values*

In all of the equations, ECT has both a negative and a positive sign, as seen in Table 8. The ECT in the N_2O equation, however, displayed a coefficient of 0.149, indicating that adjustment towards the equilibrium occurs at a rate of 14.9% annually. The ECT, on the other hand, yields a non-significant result for URP and ENGU while yielding a significant result for RGDPc, CO_2, and $RGDPC^2$.

Table 8. Error Correction Model.

Error Correction:	D(N2O)	D(CO2)	D(RGDPC)	D(RGDPC^2)	D(URP)	D(ENGU)
CointEq1	-0.149294	-0.008377	-5.620052	-215635.7	0.001124	0.096518
	(0.020395)	(0.00216)	(2.11362)	(82262.9)	(0.00092)	(0.06386)
	[-7.320290]	[-3.88557]	[-2.65897]	[-2.62130]	[1.21631]	[1.51144]

4.4.2. Results of Granger-Causality Tests

The causal relationship between the relevant factors used in this study is shown in Table 9. The results of the research demonstrate that most variables have unidirectional causal relationships. This illustrates how these factors are responsible for the significant variations in CO_2 and N_2O in Oman.

Table 9. Granger Causality Tests.

Variables	F-Stat.	p-value	Causality
RGDPc → N_2O	4.647	0.0192	Yes
N_2O → RGDPc	3.099	0.0628	No
ENGU → CO_2	16.149	0.000	Yes
CO_2 → ENGU	11.583	0.0003	Yes
URP → RGDPc	4.281	0.0252	Yes
RGDPc → URP	4.363	0.0237	Yes
URP → CO_2	0.82434	0.4501	No
CO_2 → URP	5.92209	0.0078	Yes

5. Conclusions and policy implications

In conclusion, our study examines the intricate relationship between environmental factors, particularly air pollution, and economic growth in the context of Oman. Through rigorous analysis employing cointegration and causality tests, we shed light on the multifaceted dynamics between these two critical aspects of sustainable development.

This study employed a variety of statistical methods, including OLS, cointegration tests, the Johansen Cointegration test, Granger causality analysis, and error correction modeling, to investigate the complex relationship between air pollution, CO2 emissions, and economic growth in Oman from 1990 to 2022.

Our findings reveal a strong long-term cointegration between the variables. The analysis also shows a statistically significant positive correlation between economic expansion and CO_2 emissions, as well as an annual correction of approximately 14.1% in N_2O emissions in the short-term. The Granger causality analysis indicates that CO_2, N_2O, and RGDC emissions have a unidirectional causal relationship.

Our cointegration analysis establishes the existence of a long-term equilibrium between air pollution and economic growth in Oman. This underscores the interconnectedness of the environment and the economy, highlighting the need for a balanced approach to development that considers both factors.

The causality analysis further enriches our understanding of this nexus, demonstrating a dynamic interplay where economic growth has a causal effect on air pollution, indicating that as economic activity increases, so does pollution. This implies that the pursuit of economic growth should be accompanied by a commensurate focus on environmental preservation and sustainable practices to mitigate the detrimental impact on air quality.

Conversely, we also find that air pollution can exert causal effects on economic growth, suggesting that the environmental damage inflicted by pollution can hinder the economic progress of Oman. Thus, it is imperative for the nation to prioritize environmental protection measures that reduce pollution levels, such as transitioning to cleaner energy sources and implementing stricter regulations.

Our study highlights the need for a comprehensive policy framework in Oman that reconciles environmental conservation with economic growth. This can entail investments in renewable energy, more stringent regulatory measures, and incentives for eco-friendly innovation. Moreover, our

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research stresses the significance of public awareness and participation in promoting a sustainable society that prioritizes environmental responsibility.

In summary, the interrelationship between air pollution and economic growth in Oman is a complex and dynamic one, with implications for the well-being and prosperity of the nation. Our research underscores the urgency of adopting a holistic and integrated approach that prioritizes environmental sustainability while fostering economic development. It is our hope that these findings will guide policymakers, researchers, and stakeholders in making informed decisions to ensure a cleaner, more prosperous, and sustainable future for Oman.

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