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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: The complex relationship between environmental degradation—more especially, air pollution—and economic growth in the Sultanate of Oman between 1990 and 2022 is examined in this article. To identify short- and long-term dynamics in the relationship between air pollution and economic growth, we use vector error correction models and cointegration. Additionally, Granger causality analysis is used to look into the causal relationships between these important variables. This dataset includes several control variables as well as environmental quality-related factors. The empirical findings demonstrate that the variables have a consistent long-term cointegration relationship. Furthermore, our results show that energy consumption and economic growth have a statistically significant positive effect on CO_2 emissions. Moreover, an annual adjustment of about 14.1% in N_2O emission disequilibrium is revealed by the short-term analysis. The Granger causality study shows that there are unidirectional causal linkages between CO_2 emissions, economic growth, and N_2O emissions. These results have significant policy-related ramifications for Oman. Oman has to implement strong climate change policies in order to effectively cut greenhouse gas emissions. Furthermore, as a potential replacement for conventional oil and gas resources, the government can be a key player in promoting and supporting the use of renewable energy sources like green hydrogen.

Keywords: air pollution; cointegration; Oman

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Citation: Mohammed, M.; Abdel-Gadir, S. Unveiling the Environmental–Economic Nexus: Cointegration and Causality Analysis of Air Pollution and Growth in Oman. *Sustainability* **2023**, *15*, 16918. https://doi.org/10.3390/su152416918

Academic Editors: Enrico Ferrero and Elvira Kovač-Andrić

Received: 20 October 2023
Revised: 8 December 2023
Accepted: 13 December 2023
Published: 17 December 2023

1. Introduction

In recent years, academics and decision-makers have paid close attention to the relationship between air pollution, climate change, and economic growth. It is important to highlight that a large number of "conventional" air pollution sources are also major producers of greenhouse gases (GHGs), such as CO_2, which are essential to global warming [1]. The substantial and far-reaching effects of climate change on human existence on Earth continue to be a source of concern for all people.

An unparalleled rise in the need for energy consumption has been caused by the quick development of economic activity, urbanization, and population growth. All of these things work together to cause environmental deterioration and rising greenhouse gas emissions. Consequently, attaining sustainable economic growth rates while carefully balancing this expansion with environmental preservation is one of the most important developmental concerns facing the world today. The Gulf Cooperation Council (GCC) countries' CO_2 emissions and air pollution have been the subject of numerous research projects. In the GCC countries, research shows positive relationships between energy use, urbanization, and CO_2 emissions [2].

Moreover, it has been noted that a number of meteorological factors, such as temperature, rainfall, relative humidity, wind direction, and speed, have a major impact on the amounts of hydrocarbons and CO_2 in the atmosphere [3]. The complex linkages between urbanization, energy consumption, GDP growth, foreign direct investment, financial development, and climatic conditions in the GCC countries are clarified by the combined findings of these studies [4].

Climate change is a critical topic that has prompted the calling of multiple Conferences of Parties (COPs) in an effort to assess and develop ways to reach a zero-carbon neutrality target by 2050. In keeping with the Paris Agreement's goal of keeping global warming to 1.5 °C, Oman has committed to achieving net-zero emissions by 2050. Oman is working hard on this project, with a major emphasis on building resilience and switching to sustainable energy sources. Initiatives like the second nationally determined contribution (NDC) and the National Strategy for Adaptation and Mitigation to Climate Change highlight how crucial it is to build an energy infrastructure that is resilient to the effects of climate change. Moreover, the National Energy Strategy and Oman Vision 2040 establish challenging targets for increasing renewable energies and enhancing energy efficiency.

The main goal of this article is to investigate the changing relationship between Oman's economic growth and air pollution from 1990 to 2022 in order to provide new insights into this important relationship. Moreover, examining the relationship between air pollution, economic growth, and other pertinent control variables has the potential to provide insightful viewpoints on this matter. This study was motivated in part by the fact that previous research has not explicitly examined the relationship between air pollution, climate change, and economic growth in the context of Oman.

Using a variety of econometric methods, such as dynamic ordinary least squares (DOLS) and cointegration tests, to evaluate the long-term dynamics of the variables represents our secondary methodological contribution. We also use panel Granger causality to clarify the way these variables are causally related. This article is organized as follows in the sections that follow: We offer a succinct summary of the body of research in Section 2. The approach is described in Section 3, along with data sources and variable definitions. In Section 4, the empirical results are presented. A summary of the findings and recommendations for policies are to be found in the closing section.

1.1. Greenhouse Gas Emissions in Oman

In Oman, human and natural factors account for the majority of greenhouse gas emissions [5]. Oman's emissions do contribute to global climate change, albeit being relatively lower than those of several industrialized nations. The following are Oman's main causes of greenhouse gas emissions:

1. Energy production: A major portion of Oman's greenhouse gas emissions come from the energy sector. Because the nation's economy and electricity generation are mostly dependent on oil and natural gas, fossil fuels are burned in power plants and other industrial processes, which contributes to the atmospheric release of large amounts of carbon dioxide (CO_2) [6].
2. Transportation: Due to Oman's expanding population and economy, there are more cars on the road, which means that gasoline- and diesel-powered cars are the main contributors to CO_2 emissions. The reliance on private vehicles is additionally exacerbated by the absence of a well-developed public transportation system [5].
3. Industrial processes: As a byproduct of their operation, industrial processes, including the manufacture of cement, smelting metal, and producing petrochemicals, emit greenhouse gases. CO_2 and other gases including nitrous oxide (N_2O) and methane (CH4) are among these emissions [7].
4. Waste management is essential to reducing methane emissions. Organic materials that are improperly disposed of as solid trash in landfills may break down anaerobically, producing methane. However, it is possible to reduce these emissions by putting in place appropriate waste management and recycling procedures [8,9].

In Oman's agriculture sector, the two main sources of greenhouse gas emissions are rice production and methane emissions from enteric fermentation in cattle. The application of synthetic fertilizers is another cause of nitrous oxide emission in agriculture [10,11].

5. Reductions in carbon sinks and the release of carbon stored in soils and plants can be the outcomes of changes in land use, such as urbanization and deforestation. This drop in biodiversity could have a substantial effect on the climate and ecology. The ecosystem and climate may be significantly impacted by this decline in carbon sinks [12].
6. Emissions of greenhouse gases can rise due to improper wastewater treatment system management. Better wastewater treatment systems can reduce methane emissions and improve the overall health of the environment [13].

According to the percentage of fuel burned overall, Figure 1 shows the sources of CO_2 emissions in Oman. The industrial and transportation sectors are closely ranked in order of contribution, with power production emerging as the top contributor.

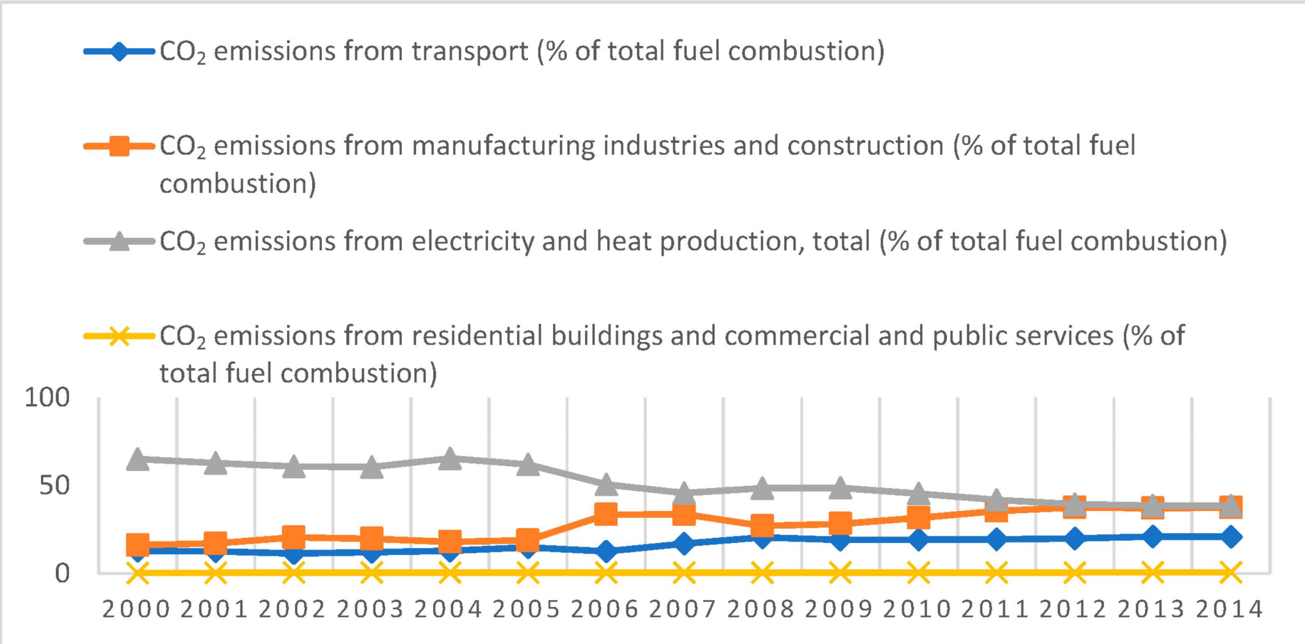

Figure 1. Sources of CO_2 emissions from energy sub-sectors in Oman. Source: World Bank, World Development Indicators, 2022.

1.2. Causes of Air Pollution in Oman

Oman's air pollution is caused by a multitude of factors, many of which are shared by urban centers and industrialized regions globally [14,15]. Some of Oman's primary contributors to air pollution include the following:

1. Industrial emissions: Processes used in the extraction of oil and gas, the production of petrochemicals, and other heavy industries discharge a range of air pollutants into the environment. These emissions include, but are not limited to, particulate matter, sulfur dioxide (SO_2), nitrogen oxides (NOx), and volatile organic compounds (VOCs).
2. Vehicle emissions: The increasing number of cars on the road exacerbates air pollution. Both gas-powered and diesel-powered vehicles emit various pollutants, such as NOx, particulate matter, carbon monoxide (CO_2), and volatile organic compounds.
3. Infrastructure building and development: As cities get more populated, there may be an increase in dust and particulate matter in the air. These particles can cause respiratory problems and reduce air quality.
4. Natural sources: Dust storms can have a major impact on air pollution, particularly in Oman's arid climate. Sand and dust particles are carried into the atmosphere and, once settled, have the potential to impact air quality.
5. Maritime transport: Oman has a sizable shipping sector due to its advantageous location close to the Arabian Sea and the Gulf of Oman. The air quality around the

shore is impacted by ship emissions, which might include sulfur dioxide, SO_2, and particulate matter.
6. Waste management: Open burning of trash and inefficient waste disposal can release pollutants back into the atmosphere. Particularly in certain less developed areas, this is a worry.
7. Oil and gas operations: As a significant producer of both, Oman may emit greenhouse gases and pollutants during the extraction and processing of these resources.
8. Refineries and petrochemical facilities: The refining and petrochemical of natural gas and oil can discharge a number of airborne pollutants.
9. Agricultural practices: Ammonia (NH_3) and other chemicals can be released back into the atmosphere during the use of fertilizers and pesticides in agriculture.
10. Power generation: Pollutants may be released back into the atmosphere when fossil fuels are burned to create energy. To lessen this cause of pollution, Oman is attempting to diversify its energy sources, particularly through renewable energy initiatives.

Nitrous oxide is a strong greenhouse gas that is released when N_2O emissions are on the rise, as seen in Figure 2. One of the main causes of ozone layer depletion and global warming is N_2O. Thus, this pattern might be connected with adverse environmental consequences, contributing to climate change.

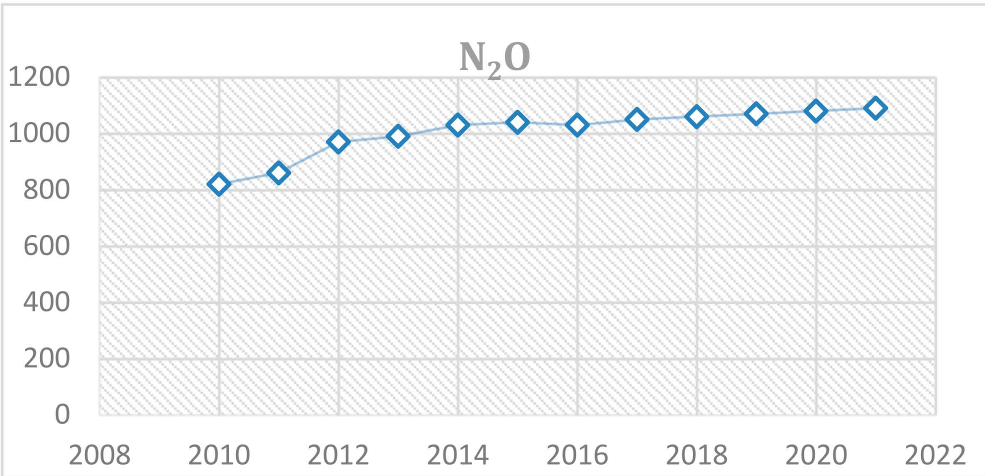

Figure 2. Trend in N_2O: 2010–2022.

2. Related Literature

2.1. Economic Growth and Air Pollution

The relationship between economic growth and air pollution has been the subject of numerous prior studies, with an emphasis on utilizing the environmental Kuznets curve (EKC) theory to analyze the long-term dynamics. The inverted U-shaped relationship between a nation's income and carbon emissions is the basis of the EKC theory. The EKC hypothesis was first put forth by [16] and seeks to investigate the relationship between environmental characteristics and per capita income. However, because their empirical research produced a wide range of results, it complicated the environmental Kuznets curve (EKC) theory. The relationship between CO_2 emissions and economic growth has also been the subject of much investigation in recent years, yielding a patchwork of conflicting and varied conclusions. For example, research by [17–22] has shown that economic growth and carbon emissions are positively correlated. Research by [23–26] has shown that, contrary to the EKC hypothesis's predictions, economic expansion eventually results in a decrease in carbon emissions. Additionally, ref. [27] carried out a thorough analysis of the relationship between Germany's exports, economic expansion, use of agricultural land, and N_2O emissions. They used time series data from 1970 to 2012 and the autoregressive distributed lag (ARDL) approach. The study's findings revealed a nonlinear, long-term correlation between greenhouse gas emissions and economic growth, supporting the existence of an environmental Kuznets curve (EKC) pattern in the German setting. We can discuss the relationship between GDP growth and air pollution by tackling this complicated subject with contradictory findings. Certain studies indicate that economic expansion may lead to an increase in air pollution, particularly if these expectations are high [28]. The decoupling between economic growth and air pollution, however, may be much improved, according to another study [29]. Research has indicated that air pollution significantly hinders China's economic expansion, underscoring the negative effects of air pollution on economic growth [30]. The relationship between economic growth and air pollution is also influenced by factors such as a country's degree of economic development, energy consumption, and industrial output as stated in [31], which gives an overview of air pollution in the MENA area [32]. The air pollutants were classified into two groups: those linked to climate change and those linked to health. They found that in the MENA region, GHS is the main pollutant that poses a risk to public health. The Gulf Cooperation Council (GCC) countries' economic growth and air pollution have been the subject of multiple articles. A favorable correlation has been found in the GCC countries between economic growth and air pollution. According to research [33,34], rising economic growth affects CO_2 emissions favorably while having a negative impact on energy use. Reduction in CO_2 emissions is achieved by energy consumption [35,36]. Long-term reduction in pollutant emissions and attainment of sustainable development can be facilitated by urbanization and the use of clean energy, as per studies [37]. Overall, the research indicates that the GCC countries' air pollution is mostly caused by economic development and energy use. The relationship between air pollution and economic growth in Oman depends on a number of different factors. Intriguing revelations have been made by recent research, such as a study by [9]. Carbon dioxide emissions have been linked, both short- and long-term, to positive shocks to capital investments, economic growth, and foreign direct investment inflows. On the other hand, as demonstrated by [38], negative shocks to economic growth and foreign direct investment inflows have been seen to cause emissions to decrease. The role of economic growth, capital investments, and foreign direct investment in Oman's efforts to reduce carbon emissions in its economy has been detailed in a prior study [38].

It is evident from the results of [9] that Oman has an environmental Kuznets curve. According to this theoretical paradigm, when a nation's economy grows, environmental quality may first deteriorate before finally improving, as academics like [36,39] have explained. With the objective of lowering carbon dioxide emissions worldwide, it is highly advised that Oman adopts green economic growth strategies in light of these findings. According to [40], this strategy entails reducing investments that have negative environmental effects while also reviving the banking industry.

2.2. Urbanization and Air Pollution

Air pollution has been proven to be significantly impacted by urbanization. Research has demonstrated that the marginal harm caused by air pollution emissions in urban areas rises as the world's population moves from rural to urban places [41]. Depending on the nation and income level, urbanization has varying effects on air pollution. PM2.5 concentrations are positively impacted by demographic urbanization, but they are negatively impacted by spatial urbanization in high-income nations and positively impacted in other nations. The opposite trend is demonstrated by social urbanization [42]. The urban form also affects PM2.5 and N_2O concentrations; aggregation index, fractal dimension, and population density are some of the elements that influence these levels. The magnitude, altitude, and density of the road network of a city determine how these factors affect it [43]. Furthermore, the growth of urban areas can modify the meteorological features of the city and reduce the ability of pollutants to diffuse, resulting in higher concentrations of pollutants [44]. The necessity for focused actions to reduce pollution and enhance air quality is highlighted by the complex and varied effects that urbanization and its numerous components have on air pollution [45]. Air pollution has increased as a result of Oman's increasing urbanization [41]. Sohar, Muscat, Sur, Salalah, and other important industrialized and urban cities in Oman are examples of local emission sources from transportation, industry, and energy producing activities [40]. In certain locations, conditions of stagnation and recirculation lead to poor air quality [46]. Furthermore, a comparison of the air quality in the two areas by [15] revealed higher levels of pollution in Kuwait's urban residential area. This suggests that high levels of air pollution may also be a result of urbanization in Oman's metropolitan areas. In order to address the issues raised by pollution associated with urbanization, it is imperative to develop sustainable urbanization practices, as stated in [34]. Finally, a number of research studies looking at the relationship between urbanization and air quality found a positive indirect effect. The rate at which people move from rural to urban areas will increase with urbanization. The quality of the air will deteriorate due to rising energy consumption and carbon emissions and [47–58], among others, have all investigated this beneficial connection.

2.3. Energy Consumption and Air Pollution

Energy use has a major influence on air pollution. Several studies have shown that using more energy, particularly fossil fuels, raises pollution levels and has negative health impacts [59,60]. Nonetheless, it has been found that utilizing renewable energy sources contributes to a decrease in air pollution [61]. Furthermore, the implementation of strict legislation and clean energy programs has been successful in improving air quality and lowering detrimental effects on health [55]. In Oman, energy usage has a big impact on air pollution [62]. In their study titled "Assessing the Influence of Clean Energy Usage and Resource Allocation on Air Pollution in China: A Spatial Econometric Analysis" the authors investigate the effects of clean energy consumption and resource allocation on air pollution in China. Their research highlights the growing concern surrounding air pollution in China and under-scores the necessity of quantifying the influence of clean energy consumption and resource allocation on pollutant levels [61].

In many emerging nations, including Oman, the introduction of energy-intensive sectors without adequate planning has resulted in air pollution being a major public health hazard [63]. Improving air quality requires reducing energy usage, as stated in [58]. It has been discovered that using renewable energy sources helps to reduce air pollution [64]. Therefore, when formulating energy and economic policies, it is crucial that the government takes into account the relationship between energy use, economic development, and environmental protection. Oman can endeavor to address its air pollution issues by enhancing energy efficiency and striking a balance between energy, economics, and environmental protection.

3. Model Specification, Data, and Econometric Methodology

3.1. Model Specification

The objective of this study is to investigate the dynamic relationship between air pollution, economic growth, and other relevant factors in Oman. The following models are used to examine how air pollution affects Oman's economic growth:

Model 1:

$$\mathrm{RGDP}c_{it} = \alpha_0 + \alpha_1\ \mathrm{CO_2} + \alpha_2\ \mathrm{N_2O} + \alpha_3\ \mathrm{ENGU_{it}} + \alpha_4 \mathrm{URP_{it}} + \varepsilon_{it} \quad (1)$$

After taking the log, model 1 becomes

$$\mathrm{LnRGDPc}_{it} = \alpha_0 + \alpha_1 \mathrm{Ln\ CO_2} + \alpha_2\ \mathrm{Ln\ N_2O} + \alpha_3\ \mathrm{Ln\ ENGU_{it}} + \alpha_4\ \mathrm{URP_{it}} + \varepsilon_{it} \quad (2)$$

where Economic growth, denoted as RGDPc, is a dependent variable. Independent variables include carbon dioxide emissions in metric tons per capita (CO_2), nitrogen dioxide (N_2O) "emitted from fossil consumption in kilotons", energy use (kg of oil equivalents 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.

Model 2:

$$N_2O_{it} = \alpha_0 + \alpha_1 \text{ RGDPc}_{it} + \alpha_2(\text{RGDPc}_{it})^2 + \alpha_3 \text{ ENGU}_{\text{it}} + \alpha_4 \text{ URP}_{\text{it}} + \varepsilon_{\text{it}} \tag{3}$$

After taking the log for both sides, model 2 becomes:

$$\text{LnN}_2\text{O} = \alpha_0 + \alpha_1\text{LnRGDP}c_{it} + \alpha_2\text{LnRGDP}ci^2 + \alpha_3\text{LnENGU}_{it} + \alpha_4\text{LnURP}_{it} + \varepsilon_{\text{it}} \tag{4}$$

where air pollution (denoted by N_2O) is a dependent variable. Independent variables include economic growth denoted by RGDPc_{it}, energy use (kg of oil equivalents 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.

3.2. Data Analysis

Following the gathering of secondary data, the model explicitly outlined the need to analyze these data. To conduct the analysis, the researchers employed Eviews 12 software Version, chosen for its flexibility and user-friendly features that facilitate tabulation, graphing, and data analysis tasks.

Detailed Definition of the Variables:

1. Economic growth (RGDPc): Denoted as RGDPc, it is the dependent variable in this study. It represents the real gross domestic product (GDP) per capita in Oman. It measures the average economic output generated by each individual in the country. It is a key indicator of the standard of living and economic well-being of a nation's population.
2. Carbon dioxide emissions (CO_2): Denoted as CO_2, they are measured in metric tons per capita. They represent the total amount of carbon dioxide gas released into the atmosphere per person in Oman. CO_2 emissions are a significant environmental variable. They are a measure of the carbon footprint associated with economic activities, particularly energy production and consumption. An increase in CO_2 emissions is often linked to industrialization and economic growth.
3. Nitrogen dioxide emissions (N_2O): Denoted as N_2O, they are measured in kilotons and represent the amount of nitrous oxide gas emitted from fossil fuel consumption in Oman. N_2O emissions are another important environmental variable. Nitrous oxide is a potent greenhouse gas and air pollutant. It is released from various human activities, including the burning of fossil fuels. Tracking N_2O emissions is crucial for assessing the environmental impact of economic activities.
4. Energy use (ENGU): Denoted as ENGU, it is measured in kilograms of oil equivalents (kgoe) per capita in Oman. ENGU represents the amount of energy consumed by an individual in Oman, typically expressed in terms of the energy equivalents of oil. It reflects the energy demand of the population and is a crucial variable when examining the relationship between energy consumption and economic growth.
5. Percentage of urban population (URP): Denoted as URP, it represents the proportion of Oman's total population living in urban areas. It is expressed as a percentage. URP is a demographic variable that reflects the level of urbanization in Oman. It indicates the extent to which the population is concentrated in urban centers as opposed to rural areas. Urbanization is often associated with economic development, as cities tend to be hubs for economic activities and job opportunities.

These comprehensive definitions provide a clear understanding of the variables under study and their significance in assessing the intricate relationships between economic growth and various environmental and demographic factors in Oman (see Table 1).

3.3. Econometric Methodology

In this study, we employ a range of econometric techniques tailored to address the specific challenges posed by time series data, causality, and cointegration.

Table 1. Variables' description and data sources.

Variable	Definition	Codes of Variable	Source
Dependent variable	Real GDP at constant 2011 national prices (Converted to the equivelant USD million, 2011)	RGDPc	PWT 10.0 *
Independent variables	CO_2 emissions (metric tons per capita) Nitrous oxide emissions (thousand metric tons of CO_2 equivalents)	CO_2 N_2O	WDI, 2022 ** WDI, 2022
Control variables	Urban population (% of the total population)	URB	WDI, 2022
	Energy use (kg of oil equivalents per capita)	ENGU	WDI, 2022

* Source: The information was taken from 1. Penn World Table, 10.0, Available at: https://www.rug.nl/ggdc/productivity/pwt/?lang=en accessed on 14 November 2023. ** World development Indicators [65].

The core econometric methodologies at our disposal include the dynamic ordinary least squares (DOLS) estimation method, the Johansen cointegration test, and the error correction model (ECM). These methodologies are well-suited for examining the long-term relationships, short-term dynamics, and causal linkages between air pollution levels and economic growth in Oman.

Dynamic ordinary least squares (DOLS)

DOLS is a method for estimating parameters in dynamic regression models with potentially integrated time series data, commonly used for cointegrated time series. The general formula for DOLS coefficients is:

$$\Delta Y_t = \alpha + \beta_1 \Delta X_t + \varepsilon_t$$

where

- ΔY_t is the dependent variable at time t;
- ΔX_t is/are the independent variable(s) at time t;
- α is the intercept;
- β is/are the coefficient(s) of the independent variable(s);
- ε_t is the error term at time t.

Johansen cointegration test

The Johansen cointegration test is a statistical method utilized to examine whether a set of time series variables exhibits cointegration, indicating a long-term relationship among them. This test is commonly employed in econometrics and involves the estimation of a vector autoregressive (VAR) model, followed by the application of likelihood ratio tests to assess the model's validity.

The Johansen cointegration test comprises two principal statistics:

1. Trace statistic (λ_trace): This statistic evaluates the null hypothesis, which suggests that the number of cointegration relationships is less than or equal to a specified value (r). It aids in determining the presence of cointegration within the dataset.
2. Maximum eigenvalue statistic (λ_max): This statistic assesses the null hypothesis that the number of cointegration relationships precisely equals a specified value (r).

To determine the appropriate number of cointegration relationships, the test is typically executed iteratively for various values of r. The results are then compared to critical values from statistical tables.

The general formula for the Johansen cointegration test statistics is as follows:

For the trace statistic (λ_trace): λ_trace = −T × ln (1 − Λ).
For the maximum eigenvalue statistic (λ_max): λ_max = −T × ln (1 − Λ_max)
Here,

- T represents the sample size, denoting the number of observations;
- Λ is the product of the (1 − p_i) terms, where p_i signifies the eigenvalues of the estimated VAR model;
- Λ_max denotes the largest eigenvalue within the estimated VAR model.

The error correction model (ECM)

The error correction model (ECM) is a framework used to analyze the short-term and long-term interactions between variables in a cointegrated relationship. The standard ECM equation takes the following form:

$$\Delta Yt = \alpha + \beta_1(\Delta Yt - 1 - \beta 2\Delta Xt - 1) + \gamma\Delta Xt + \delta 1\Delta Yt - 1 + \delta 2\Delta Xt - 1 + \varepsilon_t$$

Key components of the ECM equation include:

ΔYt: The first difference in the dependent variable at time "t", representing short-term changes.

ΔXt: The first difference in the independent variable(s) at time "t", capturing short-term changes in the independent variable(s).

α: The intercept term, signifying the short-term impact or constant effect on the dependent variable.

β1: The coefficient that measures the speed of adjustment or correction mechanism, addressing deviations from long-run equilibrium in the previous period.

β2: The coefficient related to the lagged difference in the independent variable(s), used to correct deviations from the equilibrium.

γ: The coefficient of the first difference in the independent variable(s), indicating the immediate impact of changes in independent variable(s) on the dependent variable.

δ1: The coefficient of the lagged first difference in the dependent variable, capturing any persistence or autocorrelation.

δ2: The coefficient of the lagged first difference in the independent variable(s), capturing any persistence or autocorrelation.

ε_t: The error term, representing unexplained variation in the dependent variable at time "t".

4. Results and Discussion

4.1. Descriptive Statistics

Table 2 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 2. Summary of statistics for the model variables.

Variables	Mean	Median	Max.	Min.	Std. Dev.	CV
Ln $RGDP_C$	18,747.86	19,189.55	21,458.39	14,792.32	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 3 presents the correlation matrix. The correlation matrix suggests that $RGDP_C$ has strong relationships with various factors, including a positive association with CO_2 emissions and negative associations with urbanization (URB) and nitrous oxide emissions (N_2O). These findings can be valuable for understanding the interplay between economic development, environmental factors, and urbanization in a model.

Table 3. Correlation matrix for the model variables.

Variables	RGDPC	CO_2	N_2O	URBN	ENGU
Ln $RGDP_C$	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. Results of DOLS

The results from the DOLS estimates for Model 1 and Model 2 provide valuable insights into the relationship between economic growth, climate change variables, and other control variables in the context of Oman.

Model 1: economic growth ($RGDP_C$)

To examine the association between RGDPc and climate change variables as well as other control variables, Model 1 is evaluated using the DOLS estimation method. The DOLS results presented in Table 4, reveal that:

1. The coefficient of Ln CO_2 is positive and highly significant (*t*-statistic = 8.022319, prob. = 0.0000), indicating that there is a positive association between carbon dioxide emissions (Ln CO_2) and real GDP per capita (RGDPc). This suggests that as CO_2 emissions increase, RGDPc also tends to increase, potentially highlighting a link between economic expansion and increased CO_2 emissions (the result is consistent with the results of [66,67].
2. The coefficient for Ln N_2O is negative and highly significant (*t*-statistic = −10.98754, prob. = 0.0000). This indicates a negative impact of nitrous oxide (N_2O) emissions on RGDPc. A decrease in N_2O emissions appears to be associated with higher per capita GDP.
3. The coefficient for Ln URP is positive and highly significant (*t*-statistic = 19.76856, prob. = 0.0000), indicating a positive relationship between urban population (URBN) and RGDPc. This suggests that urbanization has a significant and positive impact on economic growth.
4. The coefficient for Ln ENGU is positive but not statistically significant (*t*-statistic = 0.982604, prob. = 0.3342). This suggests that energy use (ENGU) may not have had a substantial impact on Oman's economic growth during the period under study.

Table 4. DOLS estimate of model 1: economic growth ($RGDP_C$).

Variable	Coefficient	Std. Error	*t*-Statistic	Pro.
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
Ln ENGU	12.30533	12.52318	0.982604	0.3342
R-squared	0.632001	Mean dependent var.		18,747.86
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.	34,539,276	Schwarz criterion		17.16297
Log likelihood	−267.6760	Hannan–Quinn criter.		17.04048
Durbin–Watson stat.	0.868178			

Overall, the R^2 value of 0.632001 suggests that the model explains approximately 63.20% of the variation in RGDPc.

Model 2: air pollution (N_2O)

The results of model 2 can be outlined as follows:

1. Ln $RGDP_C$: The coefficient for Ln $RGDP_C$ is positive and highly significant (*t*-statistic = 7.320290, prob. = 0.0000), indicating a positive association between real GDP per capita ($RGDP_C$) and nitrous oxide (N_2O) emissions. This supports the environmental Kuznets curve (EKC) hypothesis, suggesting that economic growth initially leads to an increase in pollution before eventually decreasing it.
2. Ln $(RGDPc_{it})^2$: The coefficient for Ln $RGDPC^2$ (quadratic term) is negative and highly significant (*t*-statistic = −5.511561, prob. = 0.0000). This quadratic term reflects the curvature in the EKC relationship, implying that, as economic growth reaches higher levels, the impact on reducing N_2O emissions becomes more pronounced.
3. Ln CO_2, Ln URP, and Ln ENGU: These variables also show significant coefficients, suggesting their influence on N_2O emissions.

In Model 2, the R^2 value of 0.986968 indicates that the model explains a substantial portion of the variation in N_2O emissions. The presence of a significant quadratic term for economic growth supports the idea of an EKC in Oman, where initial economic growth increases pollution, but at higher income levels, pollution starts to decline. This result is similar to the results obtained by [68].

Overall, the results provide evidence of a complex relationship between economic growth, climate change variables, and air pollution in Oman, with some variables having a positive impact on economic growth while others show a trade-off between growth and environmental quality, consistent with the EKC hypothesis. The findings in Table 5 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 5. DOLS estimate of model (2): air pollution (N_2O).

Variable	Coefficient	Std. Error	*t*-Statistic	Pro.
Ln $RGDP_C$	0.149294	0.020395	7.320290	0.0000
Ln $(RGDPc_{it})^2$	$\mathbf{-3.81 \times 10^{-6}}$	$\mathbf{6.92 \times 10^{-7}}$	**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
Durbin Watson (D.W).	0.875121	Akaike info criterion		9.939011
S.E. of regression	32.43592	Schwarz criterion		10.16803
Sum squared resid.	28,406.40	Hannan–Quinn criter.		10.01492
Log likelihood	−154.0242			

4.3. Unit Root Test

The outcomes of the model's series stationarity test are presented in Table 6. 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. All variables were found to be stationary for the first difference with a *p*-value of less than 0.05, except for URB and RGDPc which were integrated into order 1, I(1), and order 2, I(2), respectively.

Table 6. 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 *

* Refer to variables that are integrated of order 1, 1(1) and ** Refer to variables that are integrated of order 2, 1(2).

The results presented in Table 7 provide valuable information regarding the selection of the lag order in a VAR (vector autoregression) model. Here are some comments on the findings:

- Criteria overview: The table presents various lag order selection criteria, including log likelihood (LogL), sequential modified LR (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz information criterion (SC), and Hannan–Quinn information criterion (HQ). These criteria help determine the optimal lag order for a VAR model.
- Lag order selection: Based on the different criteria, it is clear that lag three appears to be the ideal choice for the VAR model. This is supported by the asterisks (*) in the table, indicating that lag three is the selected order by these criteria. Specifically, LR, FPE, AIC, and SC all point to lag three as the preferred choice.

Table 7. VAR lag order selection criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	23.02299	NA	6.60×10^{-5}	−1.112388	−0.980428	−1.066331
1	124.4002	180.2262	3.91×10^{-7}	−6.244458	5.716618 *	−6.060227
2	128.8578	7.181681	5.09×10^{-7}	−5.992102	−5.068382	−5.669699
3	145.3521	23.82506 *	3.46×10^{-7} *	6.408450 *	−5.088851	−5.947875 *

Note: * indicates lag order selected by the criterion.

4.4. Cointegration Test Results

4.4.1. Results of Johansen Cointegration Test

The results of the Johansen cointegration test for the variables $LnCO_2$, LnN_2O, Ln RGDPc, LnURP, and LnENGU provide insights into the long-term relationships among these variables. Cointegration analysis is essential for understanding whether there are stable relationships among these variables over time.

Here are the key findings from the Johansen cointegration test:

1. Optimal lag length: Before conducting the cointegration test, the optimal lag length was determined using the minimum Akaike information criterion (AIC) and Schwarz criterion (SC) from the estimate of the unconstrained vector autoregression (VAR) model for the first difference in the variables. It was found that the lag length is one.
2. Cointegration equations: The Johansen cointegration test was conducted since all variables are integrated at the same order, I(1) and I(2). The results indicate that there are three cointegration equations at the 5% significance level, as the trace value surpasses the critical threshold. However, the maximum eigenvalue suggests that there are only two cointegration equations.
3. Hypothesized tests: Table 8 below shows the results of various hypothesized tests. The "Trace" test statistic is used to determine the number of cointegrating equations. It indicates that there are three cointegrating equations at the 0.05 significance level.

4. Interpretation: The presence of cointegrating equations suggests that there are long-term relationships among the variables, meaning that they move together in the long run. In this analysis, one can explore these cointegrating relationships further to understand how changes in one variable affect the others in the long term.

Table 8. Johansen cointegration test 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

* denotes rejection of the hypothesis at the 0.05 level; ** MacKinnon-Haug-Michelis [69]. *p*-values.

Overall, the results of the Johansen cointegration test provide evidence of stable long-term relationships among the selected variables, which is important for conducting further analyses and drawing meaningful conclusions about the dynamics of these economic and environmental factors in Oman.

In all of the equations, ECT has both a negative and a positive sign, as seen in Table 9. 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 $RGDP_C{}^2$.

Table 9. Error correction model.

Error Correction:	D (N_2O)	D (CO_2)	D (RGDPC)	D ($RGDPc_{it}$)^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 Granger causality tests provide insights into the causal relationships among the variables considered in this study. These tests help determine the direction of causality between pairs of variables. Here is an analysis of the results from Table 10:

- RGDPc → N_2O (F-Stat. 4.647, *p*-value 0.0192, causality: yes):

Table 10. 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

There is a statistically significant unidirectional causal relationship from real GDP per capita (RGDPc) to N_2O emissions. This means that changes in RGDPc can cause significant variations in N_2O emissions in Oman.

- N_2O → RGDPc (F-Stat. 3.099, *p*-value 0.0628, causality: no):

The test suggests that there is no statistically significant causal relationship from N_2O emissions to RGDPc. In other words, changes in N_2O emissions do not significantly impact real GDP per capita in Oman.

- ENGU → CO_2 (F-Stat. 16.149, *p*-value 0.000, causality: yes):

There is a statistically significant unidirectional causal relationship from energy use (ENGU) to CO_2 emissions. This implies that variations in energy consumption significantly influence CO_2 emissions in Oman.

- CO_2 → ENGU (F-Stat. 11.583, *p*-value 0.0003, causality: yes):

There is a statistically significant unidirectional causal relationship from CO_2 emissions to energy use (ENGU). Changes in CO_2 emissions have a significant impact on energy consumption in Oman.

- URP → RGDPc (F-Stat. 4.281, *p*-value 0.0252, causality: yes):

There is a statistically significant unidirectional causal relationship from urban population (URP) to real GDP per capita (RGDPc). Changes in the urban population have a significant impact on the economic growth in Oman.

- RGDPc → URP (F-Stat. 4.363, *p*-value 0.0237, causality: yes):
- There is a statistically significant unidirectional causal relationship from real GDP per capita (RGDPc) to urban population (URP).
- URP → CO_2 (F-Stat. 0.82434, *p*-value 0.4501, causality: no):

The test suggests that there is no statistically significant causal relationship from urban population (URP) to CO_2 emissions. Changes in the urban population do not significantly impact CO_2 emissions in Oman.

- CO_2 → URP (F-Stat. 5.92209, *p*-value 0.0078, causality: yes):

There is a statistically significant unidirectional causal relationship from CO_2 emissions to urban population (URP). Changes in CO_2 emissions affect the size of the urban population in Oman.

In summary, the Granger causality test results indicate that most of the variables have unidirectional causal relationships in Oman. These findings are crucial for understanding how changes in economic growth, energy use, urban population, and emissions impact each other in the context of environmental sustainability and economic development in Oman.

5. Conclusions and Policy Implications

This study shed light on the intricate relationship between economic growth, air pollution, and environmental sustainability in Oman over the period 1990–2022. Through a comprehensive analysis employing various statistical techniques, we have uncovered valuable insights that have important policy implications for the country's future development.

Our key findings include:

1. Long-term cointegration: We have established that there is a substantial long-term cointegration among the variables, indicating a stable relationship between economic growth and air pollution in Oman.
2. Positive link between economic growth and CO_2 emissions: Our analysis has revealed a statistically significant positive association between economic growth and CO_2 emissions, suggesting that, as the economy grows, so does the level of carbon dioxide emissions.
3. N_2O emissions correction: We found that there is an annual correction rate of approximately 14.9% in N_2O emissions in the short term, indicating a dynamic adjustment towards an equilibrium.
4. Causality analysis: The Granger causality analysis has shown unidirectional causal relationships between economic growth, energy use, urban population, and emissions in Oman, emphasizing the dynamic interplay between economic activity and air pollution.

These findings have important policy implications for Oman's sustainable development:

1. Balanced development: Oman should adopt a balanced approach to development that recognizes the interdependence of the environment and the economy. Policymakers should prioritize environmental preservation alongside economic growth to ensure long-term sustainability.
2. Environmental protection initiatives: Stronger regulations, incentives for environmentally friendly innovation, and investments in renewable energy sources are crucial to reduce pollution levels and mitigate the negative impact of air pollution on economic growth.
3. Policy framework: Oman needs a comprehensive policy framework that promotes sustainable practices and environmentally responsible policies. This framework should encourage the transition to cleaner energy sources and stricter environmental standards.
4. Public engagement: It is essential to involve the general population in advancing environmental responsibility. Public awareness campaigns and education initiatives can play a significant role in fostering a culture of sustainability.

In summary, the complex and evolving relationship between air pollution and economic growth in Oman calls for a strategic and integrated approach to development. These findings provide valuable insights for stakeholders, researchers, and policymakers to make informed decisions that prioritize both economic prosperity and environmental well-being. By adopting sustainable practices and policies, Oman can secure a greener, wealthier, and more sustainable future for its citizens and the planet.

Future research directions:

Based on the findings of this paper, several promising avenues for future research emerge:

1. **Sectoral analysis**: Delve into the contribution of various economic sectors in Oman to CO_2 and N_2O emissions. This entails breaking down economic and emissions data to pinpoint which sectors are primarily responsible for the observed relationships.
2. **Environmental impact assessment**: Undertake a comprehensive assessment of the environmental impact, including ecological and health consequences, resulting from the documented air pollution in Oman. Such an evaluation can guide policymakers in setting priorities for environmental enhancements.
3. **Comparative Studies**: Conduct comparative analyses involving other Gulf region countries to discern regional disparities in the interplay between economic growth and environmental variables. This approach can uncover best practices and lessons that are applicable to Oman.

These research directions promise to advance the comprehension of the intricate relationship between economic growth and environmental factors in Oman. Consequently, they hold the potential to provide valuable insights for policymakers and stakeholders operating within the region.

Author Contributions: The conceptualization, methodology, and data analysis for the research paper were conducted by S.A.-G., while the literature review and editing were handled by M.M. The original draft was written by S.A.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare there is no conflict of interest.

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