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Investigating the Effects of Economic Factors, Renewable Energy, Innovation, and Urbanization on Environmental Sustainability: A Case Study of Middle East and North Africa Countries

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ABSTRACT

Carbon dioxide (CO_2) emissions, as the main greenhouse gas and a key factor of adverse environmental changes, have been one of the most important global challenges and the focus of researchers and policymakers in recent years. The Middle East and North Africa countries, due to the extensive production and consumption of fossil fuels and the high share of CO_2 in greenhouse gas emissions, require special study in this field. In this regard, the present study was conducted with the aim of analyzing the effect of several key economic and technological factors, including renewable electricity generation, economic complexity, innovation, financial development, and urbanization, on the environmental sustainability indicator (CO_2 emissions) in 15 countries of the study region over the period 1996 to 2022. In this study, panel model and the Driscoll-Kraay econometric technique were employed to examine the effect of these factors on CO_2 emissions. The estimation results of the model using the Driscoll-Kraay method showed that economic complexity and its squared term had no significant effect on CO_2 emissions. In contrast, urbanization had a negative and significant effect on CO_2 emissions. Electricity generation from renewable energy also had a negative and highly significant effect on CO_2 emissions. Meanwhile, innovation and financial development had a positive and significant effect on CO_2 emissions, indicating their role in increasing industrial activities and intensifying pollution. This research emphasizes the necessity of policymakers' focus on expanding renewable energy, directing innovation toward green technologies, designing sustainable financial frameworks, and implementing smart urban management. Implementing these measures can, in addition to reducing environmental impacts, pave the way for sustainable development.

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Introduction

Carbon dioxide (CO_2) emissions are among the most significant challenges facing humanity and have attracted considerable attention from researchers and policymakers in recent years. Greenhouse gases are the primary drivers of global warming and adverse environmental changes, and among these gases, CO_2 contributes the most to global warming and environmental pollution (Kivyiro & Arminen, 2014). In fact, it accounts for more than 70% of total greenhouse gas emissions worldwide (Hanif, 2018). Various studies and reports identify fossil fuel consumption as the main source of CO_2 emissions. However, CO_2 emissions and fossil fuel consumption are not uniform across regions and countries. The MENA region, which includes the Middle East and North African countries, produces approximately 39% of the world’s crude oil, natural gas, and petroleum-based fuels. The production and consumption of these resources are responsible for nearly 85% of total greenhouse gas emissions in the region. The substantial share of CO_2 in the total greenhouse gas emissions of Middle Eastern and North African countries, which results not only from energy consumption but also from fossil fuel production, highlights the necessity of conducting a more focused investigation of CO_2 emissions in this region (Mohammadi et al., 2020). This region, which is characterized by unique features compared to other regions of the world-such as limited water resources, heavy dependence on fossil fuels, and rapid population growth-faces serious challenges in maintaining environmental sustainability.

Over the past few decades, with the growing emphasis on sustainability and environmental protection, attention has increasingly shifted toward clean and renewable energy sources. This is because heat and emissions generated from the combustion of fossil fuels are among the major factors causing environmental degradation (Mohammadi, 2016). Renewable energy sources, as clean and environmentally friendly forms of energy, can play a significant role in reducing the emission of pollutants such as CO_2 and other greenhouse gases. Their environmental compatibility, contribution to reducing air pollution, renewability, and widespread availability across the world have led these energy sources to assume an increasingly large share in the global energy supply system (Fotros et al., 2012).

Given that the countries of the Middle East and North Africa region are among the world’s largest producers and consumers of energy, investigating the impact of renewable energy production on the environmental sustainability of these countries is of particular importance. In addition, due to limited water resources and rising energy demand, the countries of the Middle East and North Africa are facing severe water and energy crises. These crises pose serious threats to environmental sustainability and social welfare in the region. Therefore, the use of renewable energy sources, as a potential solution for energy supply and for reducing negative impacts on water resources, appears essential.

Nevertheless, the attainment of environmental sustainability and the effective abatement of CO_2 emissions cannot be realized solely through the expansion of clean energy generation. A growing body of empirical evidence suggests that ancillary structural factors—most notably economic complexity, technological innovation, and financial development—also exert profound and statistically significant influences on the overall environmental quality trajectory of the MENA region (Zhang et al., 2020). Economic complexity is an index that measures the diversity and complexity of a country's manufactured products and indicates extent to which a country has the ability to produce complex and advanced-technology goods. (Aghion et al., 2020). This index is calculated based on merchandise export data and the product-country allocation matrix (Hidalgo & Hausmann, 2009). Countries with higher ECI possess greater industrial and technological capacity, which can have both a positive effect (an increase in CO_2 emissions due to energy-intensive industrial activities) and a negative effect (a reduction in CO_2 through clean technologies and optimization of energy consumption) on CO_2 emissions. Therefore, in the economic context, economic complexity is one of the factors that can influence the process of renewable energy development and environmental innovations in the countries of the Middle East and North Africa region. In these oil-rich countries, financial challenges and resource scarcity for investment in new technologies are among the biggest obstacles to sustainable development (Zhang et al., 2020). In these circumstances, it appears essential to analyze how renewable energy production and technological innovations can contribute to facilitating sustainable development and reducing environmental impacts.

In addition to economic complexity, innovations in the energy sector can also drive progress in renewable energy production and improve environmental performance. The use of modern technologies in renewable energy production and storage can enable countries in the region to utilize their resources more optimally while reducing negative environmental impacts (Zhang et al., 2020). Particularly in underdeveloped and developing countries, the use of innovative technologies can help improve environmental quality and reduce environmental costs.

The innovation system is considered one of the four main pillars of the knowledge-based economy according to the World Bank's classification. This system is defined as an efficient innovation system to support the activities of businesses, research centers, and universities in order to generate and disseminate new knowledge. Based on this framework, the performance of the innovation system is measured through two key indicators. The first is the number of articles published in scientific journals, which indicates the ability to produce and disseminate scientific knowledge; the second is the number of patent applications filed by residents, which reflects the capacity to transform knowledge into technology and commercialize innovative ideas (Asadpour Kordi et al., 2024).

The countries in this region suffer severely from economic and political fluctuations, and under these circumstances, attention to innovative methods to reduce dependence on fossil fuels and improve environmental conditions is essential. Accordingly, research on renewable energy production and its impact on environmental sustainability can be considered an effective step in this direction.

Financial development is also considered a key factor in creating environmental and renewable energy infrastructure in the countries of the region. Access to sufficient financial resources for investment in clean energy projects and the development of modern technologies can help the countries in this region find effective solutions to reduce pollutants and improve environmental quality. Studies show that the countries of the Middle East and North Africa region can, by utilizing their financial resources from oil and gas exports, invest in environmental projects and renewable energy and achieve sustainable development. Financial development also provides the means to utilize environmentally friendly technologies and establish less polluting industries (Fatahi Ardakani & Sakhi, 2021).

In this regard, this study aims to comprehensively and systematically examine the impact of renewable energy production, economic complexity, innovation, and financial development on CO_2 emissions in the countries of the Middle East and North Africa region. In fact, the objective of this study is to identify the interrelationships among these factors and analyze their effects on the environmental quality of the countries in this region. Examining these variables not only helps to better understand environmental problems but can also provide practical solutions for improving the environmental conditions of the region's countries.

Finally, this study can serve as a scientific and practical model for designing energy and environmental policies in developing countries, especially in the Middle East and North Africa region. The results of this study can be used by decision-makers and policymakers in this region as an important tool in designing sustainable development strategies and reducing negative environmental impacts.

In this regard, research on the impact of renewable energy production, economic complexity, technological innovations, and financial development on environmental sustainability in the Middle East and North Africa region is not only vital for improving environmental conditions, but can also serve as a model and provide solutions for other developing countries facing similar problems.

Furthermore, research in this area can contribute to the formulation of appropriate policies for the optimal utilization of natural resources, reducing dependence on fossil fuels, and ultimately enhancing environmental quality in these countries (Zhang et al., 2020).

Particularly for countries that face economic and political challenges in addition to environmental crises, this research can serve as an effective tool in designing energy policies and sustainable development. In these countries, the existence of rich natural resources is an opportunity to utilize renewable energy while reducing negative impacts on the environment. The countries of the Middle East and North Africa region overall have specific characteristics that make research on environmental sustainability in this region of high importance. Some of the most important reasons for selecting these countries are:

Dependence on fossil resources: A large number of countries in the Middle East and North Africa region are major oil and gas producers, and they supply a major part of their energy from fossil resources. This issue causes environmental pollution and climate change, and therefore the use of renewable energy can be proposed as a sustainable and less harmful option in these countries.

Water scarcity: The countries of the Middle East and North Africa region face severe water scarcity, and this crisis has intensified, particularly during climate change. In these circumstances, the use of renewable energy can help provide energy without putting pressure on water resources. It should be noted that in the Middle East and North Africa countries, only about 3% of the region's electricity is generated from hydropower plants as water-based renewable energy sources (Mahlooji et al., 2020).

Economic and political challenges: The countries of the Middle East and North Africa region frequently face numerous economic and political challenges that affect sustainable development and the use of renewable resources. Research in this area can help identify solutions to overcome these challenges and improve the environmental conditions of these countries.

Technological and innovation opportunities: Some countries in the Middle East and North Africa region are striving to develop new and innovative technologies in the field of energy. This research can help examine the impact of technological innovations on improving environmental conditions and the optimal use of renewable energy in these countries.

Literature Review

Many studies have been conducted both domestically and internationally to examine the effects of renewable energy production, innovation, and economic factors on environmental sustainability in recent years. Among domestic studies, Amirtaimoori (2019) investigated the relationship between CO_2 emissions and financial development in Iran’s agricultural sector using annual data from 1981 to 2013 (1360–1392 in the Iranian calendar) and a Vector Autoregression (VAR) model. The results indicated that in the short run, financial development has a significant positive effect on CO_2 emissions in the agricultural sector. In the long run, energy consumption, financial development, and economic growth lead to higher CO_2 emissions, while technological progress has a reducing effect on this gas. In another study, Masoudi et al., (2020) examined the impact of technological innovation and renewable energy on CO_2 emissions in selected countries of the International Renewable Energy Agency (IRENA) using quantile regression. The findings showed that renewable energy has a negative and statistically significant effect on CO_2 emissions, whereas technological innovation has a positive and significant effect on CO_2 emissions. Moreover, this effect initially showed a declining trend but gradually shifted toward an increasing trend over time. Mohammadi et al., (2023) investigated the impact of economic complexity and renewable energy consumption on environmental pollution in developing countries. The results showed that the economic complexity index has a negative and significant effect on CO_2 emissions in these countries. Renewable energy consumption also has a significant effect on reducing CO_2 emissions. In addition, at higher levels of economic complexity, renewable energy consumption leads to an even greater reduction in CO_2

emissions. Therefore, developing countries should substantially increase the share of renewable energy through innovation processes in the energy sector, which can contribute to reducing environmental pollution in these countries. Bahraminia et al., (2024), in a study conducted on oil-exporting countries over the period 2000–2021 using a panel smooth transition regression (PSTR) model, confirmed a nonlinear relationship between financial development and CO_2 emissions. The results indicated that financial development initially increases carbon emissions; however, after passing a certain threshold, its effect becomes negative and leads to a reduction in emissions. Mansouri et al., (2025) examined the impact of energy efficiency and economic growth on CO_2 emissions in Iran over the period 1980–2021 using the Autoregressive Distributed Lag (ARDL) approach. The results showed that in the long run, energy efficiency has a positive and significant effect on CO_2 emissions. Similarly, economic growth has a positive and significant effect on CO_2 emissions.

At the global level, many countries have emphasized the use of renewable energy for energy production. A study by Nuta (2024) in Eastern European countries showed that renewable energy use and economic complexity play a positive and significant role in the decarbonization process of the selected countries. The results also indicated that economic growth and urbanization have a negative impact on decarbonization. Ma and Ogata (2024), using panel data from 136 countries over the period 1990–2020, examined the relationship between urbanization and CO_2 emissions. The findings revealed that the urbanization rate has a negative effect on CO_2 emissions. Moreover, the results showed that the carbon intensity of fossil energy consumption moderates this relationship and weakens the mitigating effect of urbanization on CO_2 emissions. Vente et al., (2024), in an innovative study, investigated the environmental impacts of research in the field of recommender systems. By replicating experimental procedures from 79 published papers between 2013 and 2023, they estimated the energy consumption and corresponding CO_2 emissions. The results showed that studies using deep learning algorithms produce on average about 3,297 kg of CO_2 equivalent, which is approximately 42 times higher than studies based on traditional methods. This level of emissions even exceeds those generated by an intercontinental flight, indicating that the development and dissemination of scientific research in energy-intensive fields can directly contribute to increased CO_2 emissions. A study by Rana et al., (2024) on thirteen Asian economies over the period 1995–2017 showed that hydropower production and technological innovation have a negative effect on environmental indicators, thereby contributing to improved environmental sustainability. In contrast, economic complexity, urbanization, and financial development were found to reduce environmental sustainability. The results also confirmed a nonlinear effect of economic complexity, supporting the Environmental Kuznets Curve (EKC) hypothesis, and identified a feedback relationship between hydropower energy and CO_2 emissions. Similarly, Wan et al., (2021), in a study in India, found that economic complexity, globalization, and renewable energy consumption play a significant role in reducing environmental degradation. In contrast, economic growth was identified as the main driver of increased pollution in both the short and long run.

A review of domestic and international studies shows that economic, financial, and technological factors play a decisive role in environmental sustainability and CO_2 emissions. In general, financial development and economic growth have often been associated with increased pollution, while renewable energy, technological innovations, and economic complexity have been effective in reducing emissions and promoting environmental sustainability. Furthermore, some research has pointed to the nonlinear relationship between economic complexity and environmental quality, confirming the Environmental Kuznets Curve hypothesis. In the context of urbanization, the results of studies show that its effect can be twofold, such that in some countries increased urbanization has led to a reduction in emissions, while in others it has exacerbated pollution. On the other hand, the results indicate that even energy-intensive scientific activities, such as deep learning-based research, can directly increase carbon emissions. Overall, moving towards clean energy, advancing technology, and efficient governance are among the most important requirements for achieving sustainable development and mitigating the effects of climate change.

This study simultaneously examines the impact of renewable energy production on environmental sustainability by considering the components of economic complexity, technological innovations, financial development, and urbanization in the countries of the Middle East and North Africa region. While many studies have focused only on the environmental or economic impacts of renewable energy production, this study addresses the interconnectedness and interaction of these factors and provides a comprehensive analysis. The novelties of this research lie in the combination of various economic, environmental, and social dimensions-especially in the context of the countries under study-the use of advanced models and new technological analyses, which can offer innovative solutions for sustainable development in this region.

Data and methodology

This study is conducted with the aim of investigating the impact of key factors including renewable energy production, economic complexity, innovation, and financial development on environmental sustainability in the 15 selected countries in the Middle East and North Africa region. Country selection was based on the availability of valid and complete data for all study variables including renewable energy, economic complexity, and CO_2 emissions during the study period (1996–2022).

Furthermore, to harmonize countries despite differences in scales and structural characteristics, this study has attempted to define the variables under investigation as comparable indicators based on their nature. Specifically, to address the issue of differences in the size of the economy or population, scale-dependent variables have been considered on a per capita basis or as relative (percentage) measures. Additionally, for composite indicators such as economic complexity and financial development, standardized and normalized values published by international institutions have been used. This approach ensures that the data are placed within a comparable framework and enables comparative analysis across countries

This research will be conducted quantitatively using panel data analysis will be employed to examine the impact of these factors on CO_2 emissions. The use of panel data provides a very rich information environment for expanding estimation methods and theoretical results. The standard form for panel models is as follows:

$$Y_{it}=\beta X_{it}+\alpha Z_i+\varepsilon_{it} \tag{1}$$

In Equation (1), Y represents the dependent variable, X denotes the explanatory variables, and Z refers to group-specific characteristics. The subscript i indicates cross-sectional units, while t represents time. The first step is to determine whether the data is pooled or panel. For this purpose, the F-Limer test, also known as the Chow test, is applied. If the data are not pooled, it is necessary to determine whether the panel model has fixed or random effects. To this end, the Hausman test is used (Rana et al., 2024).

The dependent variable is per capita CO_2 emissions. The explanatory variables include economic complexity, urbanization, financial development, renewable electricity production, and innovation. In the analysis of countries' environmental sustainability, CO_2 emissions indicator is considered a key criterion for assessing the pressure imposed on ecosystems and natural resources. Per capita CO_2 emissions are one of the most important environmental performance indicators, directly linked to industrial activities, fossil energy consumption, and economic growth patterns. This indicator is usually measured in tons per person and plays a direct role in climate change and global warming. Its data is typically extracted from reliable sources such as the World Bank. Urbanization is usually defined as the percentage of the population residing in urban areas relative to the total population. This indicator is officially reported by the World Bank and represents the physical development of cities, rural-to-urban migration, and the demand for infrastructure, energy, and transportation in urban areas. Financial development is a multidimensional concept that refers to the quality, efficiency, accessibility, and depth of a country's financial markets and institutions. The International Monetary Fund has designed a composite financial development index for more precise measurement of this variable, which covers both the banking sector and the capital market. In this study, renewable energy production is measured based on electricity generated from renewable sources. This indicator includes electricity generated from sources such as solar, wind, hydro, geothermal, and biomass energy, and is reported annually in billion kilowatt-hours. The innovation variable is also considered one of the key factors affecting environmental sustainability and technological development of countries. As stated, the two main indicators of the innovation system from the World Bank's perspective include the number of scientific articles and the number of patent applications. Due to incomplete data on patent registrations during the study period for some countries, this study uses only the number of scientific articles as the innovation indicator. This variable is measured based on World Bank data, which uses the number of scientific and technical articles published in indexed international journals as a representative of countries' scientific and research capacity. The complexity of an economy depends on the abundance of useful knowledge accumulated in that country. Economic complexity is expressed in terms of the composition of a country's manufactured products and reflects the structures that have emerged to maintain and combine knowledge. Complex economies are those that can store and connect very large amounts of relevant knowledge across large human networks to produce diverse products. In contrast, simpler economies are countries that possess productive knowledge and produce fewer and simpler products that require smaller networks for interaction (Hausmann, 2014). The Atlas of Economic Complexity is derived from international trade data, and the reason for this choice is that it is the only available dataset that provides highly detailed and rich information, linking countries to their products in a standard classification (Mohammadi et al., 2024).

The regression model of the study is specified as Equation (2) (Rana et al., 2024):

$$\ln CO_{2it} = \gamma_0 + \gamma_1 \ln ECI_{it} + \gamma_2 \ln ECI_{it}^2 + \gamma_3 \ln URB_{it} + \gamma_4 \ln STJA_{it} + \gamma_5 \ln RE_{it} + \gamma_6 \ln FDI_{it} + \mu_{it} \quad (2)$$

In Equation (2), CO_2 represents per capita CO_2 emissions as the dependent variable. ECI denotes economic complexity, and ECI^2 is the square of economic complexity, which is included in the model to test the existence of a nonlinear relationship in the form of the Environmental Kuznets Curve (EKC) in the selected countries. URB and STJA represent urbanization and innovation (per capita scientific and technical publications), respectively. FDI and RE indicate the financial development index and per capita electricity production from renewable energy sources. ln denotes the natural logarithm of the variables, γ_0 represents the intercept, and γ_1 to γ_6 represent the coefficients of the variables. μ represents the error term in Equation (2). The natural logarithm transformation (ln) of variables in the regression model has been selected for both theoretical and methodological reasons. First, using natural logarithms allows for the interpretation of coefficients in terms of elasticities (percentage changes), rather than absolute changes in CO_2 emissions per capita, which is standard in environmental and energy economics literature (Gujarati & Porter, 2009; Wooldridge, 2016). Second, logarithmic transformation helps reduce data dispersion and heteroskedasticity, thereby improving econometric estimations in long-run panel data analysis (Baltagi, 2021).

As previously stated, the square of economic complexity (ECI^2) is included to test the Environmental Kuznets Curve (EKC) hypothesis. This nonlinear specification allows for identifying the relationship between economic-technological development and environmental pollution based on the EKC theory. Specifically, a positive coefficient for ECI and a negative coefficient for ECI^2 indicate an inverted U-shaped relationship between economic complexity and CO_2 emissions (Grossman & Krueger, 1995; Dinda, 2004). This functional form is particularly appropriate for modeling nonlinear effects and examining the trade-off between industrial development and environmental protection in oil-rich and developing countries.

The choice of this functional form over simple linear or log-log models without a squared term offers several important advantages:

- It allows for the analysis of elasticity-based (percentage) effects of variables on CO_2 emissions.
- It enables the identification of nonlinear effects of economic complexity and other macroeconomic variables (urbanization, innovation, and renewable energy).
- It improves the robustness and accuracy of econometric estimations in the presence of long-term data fluctuations.

The use of logarithmic transformation combined with squared terms of economic and technological development variables is also widely applied in reputable international studies. For instance, the seminal works on the Environmental Kuznets Curve (EKC) by Grossman & Krueger (1995) and Dinda (2004), as well as studies on economic complexity and environmental performance by Aghion et al., (2016), have reported similar specifications. Moreover, in widely recognized econometrics and environmental economics textbooks such as Gujarati & Porter (2009), Wooldridge (2016), and Baltagi (2021), the rationale for using natural logarithms and testing nonlinear relationships among variables is clearly explained and well established.

Identifying the characteristics of the data is essential for selecting an appropriate econometric approach to examine the proposed relationship among variables. Accordingly, the econometric analysis of the present study begins with diagnostic tests, including cross-sectional dependence (CD), unit root, and cointegration tests, and ultimately proceeds to regression estimation methods. In this regard, three tests are employed to examine the existence of cross-sectional dependence in the data, namely the Pesaran (2007) test, the Friedman (1937) test, and the Breusch–Pagan test. These tests are used due to the potential presence of cross-sectional dependence in panel data, which may arise from interconnections among countries due to spatial effects, socio-economic networks, and other unobserved factors. Therefore, ignoring cross-sectional dependence in panel data may lead to biased and misleading results. Similarly, conducting unit root tests is also necessary to avoid the problem of spurious regression. In this study, the Levin–Lin–Chu test and the Pesaran unit root test are used to examine stationarity.

In the next step, the relationship specified in Equation (2) is estimated using the Driscoll–Kraay (DK) method (Driscoll & Kraay, 1998). This approach is a robust estimator in the presence of common econometric panel data problems such as within-unit autocorrelation, heteroskedasticity, and cross-sectional dependence among units (Hoechle, 2007).

If the panel model is specified as Equation (3):

$$y_{it}=\beta X_{it}+\mu_i+i \qquad \varepsilon_{it}=1,\dots, t, \quad N=1,\dots,T; \tag{3}$$

denotes the matrix of explanatory variables, including $lnECI_{it}$, $lnECI_{it}^{\wedge 2}$, $lnURB_{it}$, $lnSTJA_{it}$, $lnRE_{it}$, and $lnFDI_{it}$. β is the vector of regression coefficients, μ_i represents the country-specific fixed effects, and ε_{it} denotes the idiosyncratic error term. Under conditions where ε_{it} exhibits within-unit autocorrelation ($Cov(\varepsilon_{it}, \varepsilon_{is}) \neq 0$), heteroskedasticity ($Var(\varepsilon_{it}) = \sigma^2$), and cross-sectional dependence ($Cov(\varepsilon_{it}, \varepsilon_{jt}) \neq 0,\ i \neq j$), traditional methods such as OLS or FE may produce biased standard errors and unreliable inference.

The Driscoll–Kraay method corrects for these issues by using a robust covariance matrix estimator. The DK covariance estimator is specified as Equation (4):

$$\hat{V}_{DK}\hat{\beta} = (XX')^{-1}\left(\sum_{t=-T}^{T} w_t \hat{\Gamma}_t\right)(XX')^{-1} \tag{4}$$

This method allows the estimation of statistically significant coefficients and robust standard errors that are consistent in the presence of cross-sectional dependence and heteroskedasticity. Therefore, it has been widely applied in environmental and energy studies using panel data across multiple countries (Hoechle, 2007; Cameron & Trivedi, 2005).

Results and discussion

Table (1) presents the descriptive statistics related to the variables used in the research model. These statistics include the mean, minimum and maximum values, and standard deviation, which were calculated using Excel 2021 software and provide a better understanding of the data characteristics and a description of the overall status of each variable. The analysis of these indicators plays an important role in interpreting the model results and helps to understand the behavior of the variables and compare them with each other. It should also be noted that all tests and estimations related to the econometric section of the study were conducted using Stata 18 software.

Table 1. Descriptive Statistics of the Variables Used in the Research Model

Variables	Symbol	Unit	Source	Maximum	Minimum	Mean	Standard Deviation
Per capita carbon dioxide emissions	CO2	Tons of CO_2 equivalent per capita	World Bank (World Development Indicators)	53.598	0.31	12.817	13.363
Economic Complexity Index	ECI	–	Atlas of Economic Complexity	3.819	0.381	1.771	0.709
Urban population	URB	Percent	World Bank (World Development Indicators)	100	24.249	74.944	19.272
Financial Development Index	FDI	–	International Monetary Fund (IMF)	0.64	0.09	0.348	0.137
Per capita scientific and technical journal articles	STJA	Number of articles per capita	World Bank (World Development Indicators)	0.0016	0.00001	0.00026	0.00035
Per capita electricity generation from renewable energy	RE	Kilowatt-hours per capita	International Energy Agency (IEA)	800	0.01	69	100

Source: Research findings.

The analysis of the descriptive statistics of the study variables, including per capita CO_2 emissions, the economic complexity index, urban population, the financial development index, the innovation index (per capita number of published scientific and technical articles), and electricity production from renewable energy sources, reveals considerable variation among the countries under review during the period 1996 to 2022. These differences are reflected in the minimum, maximum, and standard deviation values of the variables, indicating structural, economic, and technological disparities among the countries. This variation in the data contributes to the econometric analysis by enabling more accurate coefficient estimation and the application of robust standard errors that account for heteroskedasticity and autocorrelation. However, this diversity alone does not justify the necessity of the study; rather, the importance of the research arises from the high level of CO_2 emissions and the significance of their environmental consequences in the Middle East and North Africa region. It should also be noted that, by employing a fixed effects panel model together with the robust Driscoll–Kraay estimator, it is possible to analyze the average regional effects of economic, energy, and technological variables on CO_2 emissions. Nevertheless, the model results should not be interpreted as implying uniform policy recommendations for all countries, and practical policy measures should be adapted to the specific conditions of each country.

Table (2) presents the results of the cross-sectional dependence (CD) tests.

Table 2. Results of Cross-Sectional Dependence (CD) Tests

Tests	Statistic	Probability
Pesaran	3.358	0.000
Friedman	44.484	0.000
Breusch–Pagan	490.163	0.000

Source: Research findings.

To examine the existence of cross-sectional dependence among the sample units, the Pesaran, Friedman, and Breusch–Pagan tests were employed. The results indicate that all three tests reject the null hypothesis of no cross-sectional dependence at the 1% significance level (the probability values for all tests are less than 0.01). The statistics obtained from the Pesaran, Friedman, and Breusch–Pagan tests reveal the presence of strong dependence among the cross-sectional units.

These findings suggest that interdependence and mutual interactions exist among the countries under investigation, and therefore the assumption of cross-sectional independence is rejected. Consequently, it is necessary to use estimation methods that control for cross-sectional dependence, namely the Driscoll–Kraay method, in order to obtain valid and reliable estimations.

Given the existence of cross-sectional dependence among the cross-sectional units, unit root tests are subsequently conducted on the model variables in order to ensure their stationarity and avoid misleading results. The results of the stationarity tests are reported to determine the order of integration of the variables and to select the appropriate estimation method. Table (3) presents the results of the Levin–Lin–Chu and Pesaran unit root tests.

Table 3. Results of the Levin–Lin–Chu and Pesaran Unit Root Tests

Variables	LLC (level)	p-value	IPS (level)	p-value	LLC (first diff.)	p-value	IPS (first diff.)	p-value
LnCO2	-1.869	0.030	-1.954	0.023	-4.588	0.000	-5.304	0.000
lnECI	-1.056	0.145	-1.316	0.094	-10.997	0.000	-14.026	0.000
lnFDI	1.132	0.871	0.869	1.125	-4.135	0.000	-8.248	0.000
lnURB	-2.620	0.004	-1.990	0.022	-2.914	0.000	-2.965	0.000
lnSTJA	0.383	0.649	5.057	1.000	-2.113	0.000	-4.794	0.000
lnRE	2.976	0.998	4.659	1.000	-2.063	0.019	-4.092	0.000

Source: Research findings.

To examine the stationarity of the research variables, panel unit root tests including the Levin–Lin–Chu (LLC) and Im, Pesaran, and Shin (IPS) tests were employed. The results of these tests indicate that the logarithm of CO_2 emissions (LCO_2) and the logarithm of urbanization (LURB) are stationary at the 95% confidence level in their level form. In contrast, the other variables, including the logarithm of economic complexity (LECI), the logarithm of financial development (LFDI), the logarithm of technology (LSTJA), and the logarithm of renewable energy (LRE), contain a unit root at level form, but their stationarity is confirmed after taking the first difference.

Accordingly, it can be concluded that the variables used in this study consist of a combination of stationary processes at level form (I(0)) and non-stationary processes that become stationary after first differencing (I(1)). Therefore, to avoid spurious estimations and to select an appropriate estimation method, examining the existence of cointegration among the variables appears to be necessary.

Table 4. Results of Pedroni Cointegration Test

Statistic Name	Test Statistic	Probability	Test Result
Panel PP Statistic	-3.357	0.000	Reject the null hypothesis and confirm cointegration
Panel ADF Statistic	-2.511	0.006	Reject the null hypothesis and confirm cointegration
Group PP Statistic	-5.345	0.000	Reject the null hypothesis and confirm cointegration
Group ADF Statistic	-2.848	0.002	Reject the null hypothesis and confirm cointegration

Source: Research findings.

To examine the existence of a long-run cointegration relationship among the model variables, the Pedroni panel cointegration test was applied. The results indicate that for all panel and group statistics, the probability values are below the 5% significance level, leading to the rejection of the null hypothesis of no cointegration.

These findings confirm the existence of a long-run equilibrium relationship among the variables in the model. In other words, although the variables may be non-stationary in levels, they tend to move together and converge toward a common long-run equilibrium over time. Therefore, the model estimation should account for this long-run relationship to provide more reliable and robust results.

Given the existence of a cointegration relationship among the variables, the next step involves selecting the appropriate estimation model using the F-Limer and Hausman tests. Subsequently, the estimated model will be presented using the Driscoll–Kraay robust standard errors approach to control for cross-sectional dependence.

Table 5. Results of the F-Limer and Hausman Tests

Tests	Statistic Value	Probability
F-Limer	329.397	0.000
Hausman	75.94	0.000

Source: Research findings.

The results of the F-Limer test indicate that the test statistics are 329.397 and the probability value is less than 0.01. Therefore, the null hypothesis of no fixed effects is rejected, and the fixed effects model is preferred over the pooled OLS model.

Furthermore, the results of the Hausman test, with a statistic of 75.94 and a probability value of less than 0.01, reject the null hypothesis that the random effects model is appropriate. Accordingly, the fixed effects model is preferred over the random effects model. Based on these results, the fixed effects model is selected and used to estimate the relationship among the variables in this study.

Given the results of the F-Limer and Hausman tests, which confirm the fixed effects model as the appropriate specification for the panel data, the model is estimated using Driscoll–Kraay robust standard errors. This approach provides more reliable and accurate estimates within the fixed effects framework due to its ability to simultaneously control cross-sectional dependence, heteroskedasticity, and autocorrelation. Therefore, the use of this statistical method, alongside the selection of the fixed effects model, ensures both logical and statistical consistency in the empirical analysis of the study.

Table 6. Driscoll–Kraay Estimation Results

Variable	Coefficient	DK Std. Err	t-statistic	P-value	95% Confidence Interval
LECI	0.0477	0.0954	0.80	0.429	[-0.074 , 0.170]
$LECI^2$	-0.0785	0.0758	-1.04	0.311	[-0.234 , 0.077]
LURB	-0.732	0.360	-2.03	0.053	[-1.474 , 0.010]
LRE	-0.0416	0.003	-12.45	0.000	[-0.048 , -0.034]
LSTJA	0.1607	0.022	7.29	0.000	[0.115 , 0.206]
LFDI	0.215	0.043	4.91	0.000	[0.124 , 0.305]
Constant	5.965	1.638	3.64	0.001	[2.591 , 9.339]

Source: Research findings

The Driscoll–Kraay estimation results indicate that the economic complexity variable (LECI) has a positive and statistically insignificant coefficient, meaning that no significant effect on CO_2 emissions is observed. Although the coefficient of $LECI^2$ is negative—consistent with the EKC hypothesis—it is not statistically significant, providing no empirical support for a nonlinear relationship in this sample. The urbanization variable (LURB) has a negative and statistically significant effect at the 10% level, indicating that an increase in the share of urban population can to some extent reduce CO_2 emissions. The renewable energy variable (LRE) shows a negative and highly significant effect at the 1% level, implying that greater use of clean energy leads to a reduction in greenhouse gas emissions. The technology variable (LSTJA) has a positive and statistically significant effect on CO_2 emissions, suggesting that technological advancement is associated with higher emissions. Financial development (LFDI) has a positive and statistically significant effect at the 1% level, indicating that financial development may be associated with increased industrial activity, thereby leading to higher carbon emissions.

Electricity generation from renewable energy sources has a negative and statistically significant effect on per capita CO_2emissions. This finding is consistent with the logic of substituting fossil fuels, reducing the carbon intensity of the energy mix, and aligns with previous empirical evidence reported by Masoudi et al., (2020), Mohammadi et al., (2023), Nuta (2024), and Rana et al., (2024). The urbanization rate also shows a negative and significant coefficient, which can be explained by economies of agglomeration, the expansion of public transportation systems, and more compact urban development patterns. This result is consistent with the findings of Ma and Ogata (2024). In contrast, innovation has a positive and significant effect on CO_2 emissions, which is consistent with Vente et al., (2024) and Masoudi et al., (2020). Finally, economic factors (financial development index) show a positive and significant effect on CO_2 emissions. This positive impact can be explained through several theoretical and empirical channels:

Facilitation of capital access and expansion of industrial activities: Financial development and improved access to credit facilitate investment in industrial sectors and energy infrastructure. In the Middle East and North Africa region, a large share of such investments is still directed toward conventional technologies and fossil fuel-based energy systems, thereby increasing CO_2 emissions (Wan et al., 2021; Amirtaimoori, 2019).

Scale effect: Financial development stimulates economic growth, leading to higher production and energy consumption. In the short run, the scale effect dominates, and increased economic and industrial activity is associated with higher emissions (Grossman & Krueger, 1995; Dinda, 2004).

Lack of green financial and environmental frameworks: In the absence of supportive policies and frameworks for low-carbon investment, financial development tends to increase investment in high-emission activities.

Therefore, the positive effect of financial development on CO_2 emissions is driven by increased investment in high-emission industrial and energy sectors, the dominance of the scale effect, and the absence of green financial support mechanisms. These findings align with previous evidence reported by Wan et al., (2021), Nuta (2024), Rana et al., (2024), Mansouri et al., (2025), and Amirtaimoori (2019).

Conclusion and policy implications

Given the serious environmental challenges and increasing global concerns about climate change, investigating the factors affecting environmental sustainability in sensitive and densely populated regions such as the Middle East and North Africa countries has gained great importance. This region, due to its heavy dependence on fossil energy resources, rapid population growth, and economic developments, is exposed to numerous environmental risks that can negatively impact sustainable development and quality of life. In this regard, the present study was conducted with the aim of analyzing the impact of several key economic and technological factors, including renewable energy production, economic complexity, innovation, financial development, and urban population on the CO_2 emissionsin 15 countries of the studied region during the period 1996 to 2022.

The necessity of conducting this study arises from the fact that a more precise understanding of the role of these variables can help policymakers adopt effective strategies to reduce negative environmental impacts and accelerate sustainable development in the region. Furthermore, due to the complexity of economic structures and the diversity of energy resources in the studied countries, the results of this research can offer new perspectives for improving environmental performance and developing clean technologies. Therefore, the main objective of this study was to investigate the impact of several key economic and technological factors, including renewable energy production, economic complexity and its square, the innovation index, financial development, and urban population on environmental sustainability in the studied countries. Panel data analysis of fifteen selected countries in the region, including Iran, over the period 1996 to 2022 was conducted using advanced statistical methods, including estimation with Driscoll-Kraay standard errors, to correct for issues of collinearity and autocorrelation. The key findings of this research are as follows:

Renewable energy production, as one of the key variables of the study, had a negative and significant effect on CO_2 emissions. This result indicates that an increase in the share of renewable energy in the energy mix of the studied countries has led to a reduction in greenhouse gas emissions, and this demonstrates the high capacity of clean energy to support sustainable development goals in this region. From a policy perspective, this finding highlights the necessity of encouraging investments in clean energy technologies and establishing the necessary infrastructure for the expansion of renewable energy sources.

The innovation index unexpectedly had a positive effect on CO_2 emissions; that is, the current innovations in the studied countries are more associated with energy-intensive and polluting technologies rather than green technologies. This finding suggests that innovation has not yet been sufficiently directed toward clean and environmentally friendly technologies, and policymakers need to design special supportive frameworks for the development of green innovations.

Financial development also had a positive and significant effect on CO_2 emissions, indicating that financial development without considering environmental criteria can lead to the growth of highly polluting economic activities. This issue emphasizes the importance of designing sustainable financial policies that, in addition to attracting capital, ensure green development and reduce negative environmental impacts.

Urban population showed a negative and near-significant effect on CO_2 emissions. This finding should not be interpreted as a widespread concentration of clean technologies in cities, but rather indicates the potential benefits of urbanization in energy efficiency and emission reduction through better access to infrastructure and urban services. In other words, although innovation is currently focused on polluting technologies, urbanization can have a reducing effect on emissions through energy consumption optimization, development of public transportation, and intelligent urban management. This near-significant effect also indicates the need for more detailed research and greater focus on directing innovation toward green technologies in urban areas.

Economic complexity and its square had no significant effect on CO_2 emissions. This may be explained by the resource-dependent nature of the region's economies, which rely heavily on fossil fuels and lack the diversified industrial structures seen in advanced countries.Therefore, the non-linear relationship between economic complexity and environmental pollution in this region may be weaker or different.

Based on the findings of the present study, the following policy recommendations are suggested:

- Renewable energy development should be prioritized through financial incentives, banking facilities, and R&D support for clean technologies.
- Innovation policies should be revised to promote environmentally friendly technologies, including targeted R&D investment, clean patent registration incentives, and support for sustainable-tech startups.
- Financial development frameworks should incorporate environmental sustainability principles to channel investments toward low-polluting industries and modern technologies**.**

Smart urban management and the development of sustainable infrastructure should be planned in such a way that the positive effects of urbanization on optimal energy consumption and pollution reduction are strengthened.

Future research should consider: Conducting broader comparative studies with a focus on economic structure, the type of industries, and the share of energy sources in the countries of the region for a more precise analysis of the relationship between economic complexity and environmental sustainability.

Analyzing the role of green innovation policies in developing countries and identifying the factors of their success or obstacles.

Investigating the long-term effects of sustainable financial development and green financial instruments (such as green bonds) on improving environmental indicators.

Examining the interactive and simultaneous effects of multiple environmental and economic factors using more dynamic and complex models.

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Author Contributions

The first author conceived and designed the research based on the approved research project, conducted the data analysis, interpreted the findings, drew the conclusions, and prepared the original manuscript. The second author critically reviewed and revised the manuscript. The third author contributed to the English editing and language refinement of the manuscript. The fourth author was responsible for data collection, conducting the literature review, and developing the theoretical framework of the study. All authors read and approved the final version of the manuscript

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request

Ethical considerations

The authors conducted this research in accordance with accepted ethical standards in scientific publishing. They avoided data fabrication, data falsification, plagiarism, and any form of research misconduct.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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چکیده

انتشار دی‌اکسیدکربن، به‌عنوان مهم‌ترین گاز گلخانه‌ای و عامل اصلی تغییرات نامطلوب زیست‌محیطی، یکی از جدی‌ترین چالش‌های جهانی به شمار می‌رود و همواره کانون توجه پژوهشگران و سیاست‌گذاران بوده است. کشورهای خاورمیانه و شمال آفریقا به دلیل تولید و مصرف گسترده سوخت‌های فسیلی و سهم بالای دی‌اکسیدکربن در انتشار گازهای گلخانه‌ای، نیازمند مطالعه‌ای ویژه در این حوزه‌اند. ازاین‌رو، پژوهش حاضر با هدف تحلیل تأثیر چند عامل کلیدی اقتصادی و فناورانه شامل تولید برق از انرژی تجدیدپذیر، پیچیدگی اقتصادی، نوآوری، توسعه مالی و شهرنشینی بر شاخص پایداری محیط زیست (انتشار دی‌اکسیدکربن) در ۱۵ کشور منتخب منطقه طی بازه زمانی ۱۹۹۶ تا ۲۰۲۲ انجام شد. برای این منظور، از الگوی پنل و تکنیک اقتصادسنجی Driscoll-Kraay استفاده شد. نتایج برآورد مدل نشان داد پیچیدگی اقتصادی و توان دوم آن اثری معنادار بر انتشار دی‌اکسیدکربن ندارند. در مقابل، شهرنشینی اثر منفی و معنادار بر انتشار دی‌اکسیدکربن نشان داد. تولید برق از انرژی‌های تجدیدپذیر نیز اثر منفی و بسیار معنادار بر انتشار دی‌اکسیدکربن نشان داد. درحالی‌که نوآوری و توسعه مالی تأثیر مثبت و معناداری بر انتشار دی‌اکسیدکربن داشتند که بیانگر نقش آن‌ها در افزایش فعالیت‌های صنعتی و تشدید آلودگی است. این پژوهش بر ضرورت تمرکز سیاست‌گذاران بر گسترش انرژی‌های تجدیدپذیر، هدایت نوآوری به سمت فناوری‌های سبز، طراحی چارچوب‌های مالی پایدار و مدیریت شهری هوشمند تأکید دارد. اجرای این اقدامات می‌تواند ضمن کاهش آثار زیست‌محیطی، مسیر توسعه پایدار را هموار سازد.

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