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Digital Economy and Environmental Sustainability in MENA Region: The Role of ICT and Economic Complexity

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Abstract

Purpose – This paper investigates the determinants of the ecological footprint in the Middle East and North Africa (MENA) region over the period 1995–2023. It focuses on examining the roles of economic complexity, ICT exports, GDP per capita, population density, foreign direct investment, and ICT imports in shaping environmental pressures within a short-run and contemporaneous analytical framework.

Design/Methodology/Approach – The study employs a panel data approach based on stationary transformations of the variables to ensure econometric validity and avoid spurious regression. The empirical analysis is conducted using Fixed-Effects (FEM), Random-Effects (REM), Pooled OLS, and Mixed-Effects Generalized Linear Model (GLM) estimators. These complementary models allow for the examination of short-run dynamics while accounting for heterogeneity and cross-sectional dependence across countries.

Findings – The results indicate that ICT exports consistently contribute to reducing the ecological footprint, highlighting the role of technological advancement in improving environmental sustainability. Economic complexity shows mixed effects across model specifications, reflecting transitional dynamics in structural transformation. In contrast, GDP per capita emerges as a strong and robust driver of ecological pressure, while population density contributes to environmental strain in several cases. Foreign direct investment (FDI) and ICT imports do not exhibit statistically significant effects, suggesting that their environmental impact depends on contextual factors such as institutional quality and absorptive capacity.

Implications – The findings suggest that MENA policymakers should promote ICT exports, digital infrastructure, and green technological upgrading as tools for reducing ecological pressure. At the same time, economic growth strategies should be accompanied by environmental regulation, sustainable urban planning, and green investment policies to prevent short-run income growth from increasing ecological degradation.

Originality/Value – This study contributes to the literature by providing a consistent econometric framework based on stationary panel estimations, avoiding reliance on cointegration-based methods in the presence of mixed integration orders. It offers new insights into the short-run relationships between digital transformation, economic structure, and environmental sustainability in the MENA region, a context characterized by rapid economic growth and technological change.

Keywords: Ecological Footprint; Economic Complexity; ICT Exports; GDP per Capita; Population Density; Foreign Direct Investment; ICT Imports; MENA Region; Sustainable Development

JEL Classifications: Q56; O13; F63

1 Introduction

The Middle East and North Africa (MENA) region has experienced substantial economic growth in recent decades, but it also faces significant challenges in balancing development with environmental sustainability. Characterized by rapid urbanization, high reliance on fossil fuels, and ongoing efforts toward economic diversification, the region presents a unique context for examining ecological pressures. As economic activities expand, environmental concerns have become increasingly central to both policy and academic debates. One of the most widely used indicators to measure environmental impact is the Ecological Footprint, which captures the amount of land and natural resources required to sustain human consumption patterns (Wackernagel et al., 2002). Understanding the determinants of ecological footprint is therefore essential to ensure that economic progress does not come at the expense of environmental sustainability.

This study investigates the relationship between the ecological footprint and key economic, social, and demographic variables in the MENA region over the period 1995–2023. Specifically, it examines the roles of economic complexity, ICT exports and imports, GDP per capita, population density, and foreign direct investment (FDI) in shaping environmental pressures. Unlike approaches that focus on long-run equilibrium relationships, this study adopts a stationary panel data framework to analyze short-run and contemporaneous dynamics, ensuring econometric validity in the presence of mixed integration orders among variables.

The empirical analysis employs a set of complementary panel estimation techniques, including Fixed-Effects (FEM), Random-Effects (REM), Pooled OLS, and Mixed-Effects Generalized Linear Model (GLM). These methods allow for a comprehensive assessment of the relationships between economic factors and environmental outcomes while accounting for heterogeneity across countries and potential cross-sectional dependence. By relying on stationary transformations of the data, the study avoids spurious regression issues and provides robust empirical evidence on the short-run determinants of ecological footprint.

From a theoretical perspective, previous studies suggest that more complex economies are better positioned to reduce environmental degradation through innovation, diversification, and the adoption of cleaner technologies (Chu, 2021; Sbardella et al., 2018). Similarly, ICT development has been found to enhance environmental sustainability by improving energy efficiency and supporting digital solutions that reduce resource consumption (Asongu et al., 2018; Salahuddin & Alam, 2016). However, the empirical evidence remains mixed, particularly in regions such as MENA, where economic structures, institutional quality, and technological capabilities vary significantly across countries.

By examining the interconnections between economic development, technological transformation, and environmental sustainability, this study aims to provide policy-relevant insights that can help decouple economic growth from environmental degradation. In doing so, it contributes to the broader literature on sustainable development by offering a data-driven analysis of ecological pressures in a region characterized by rapid structural change and environmental vulnerability.

This study contributes to the literature in several ways. First, it focuses on economic complexity and ICT trade as key determinants of ecological footprint in the MENA region, an area that remains relatively underexplored. Second, it distinguishes between ICT exports and imports, providing a more nuanced understanding of the role of digital transformation in environmental sustainability. Third, it adopts a consistent econometric framework based on stationary panel estimations, avoiding reliance on cointegration-based methods and ensuring robust inference in the presence of mixed integration orders. These contributions provide new insights into how economic and technological factors interact to influence environmental outcomes in the MENA region (e.g., Abid, 2025a).

The remainder of the paper is structured as follows. Section 2 presents the theoretical framework underpinning the analysis. Section 3 reviews the relevant literature. Section 4 describes the data and methodology. Section 5 reports the empirical results. Section 6 discusses the findings and their policy implications. Section 7 concludes the study and outlines directions for future research.

2 Theoretical Framework

The relationship between economic development and environmental sustainability has been widely analyzed through several theoretical frameworks, notably the Environmental Kuznets Curve (EKC), economic complexity theory, and technology diffusion mechanisms. These frameworks provide the conceptual foundation for understanding how economic, technological, and demographic factors influence ecological footprint dynamics in the MENA region.

2.1 Environmental Kuznets Curve (EKC)

The relationship between economic growth and environmental degradation is often analyzed through the Environmental Kuznets Curve (EKC) hypothesis, which suggests a nonlinear (inverted U-shaped) relationship between income and environmental pressure. However, testing such nonlinearity requires the inclusion of a quadratic income term and is typically more appropriate in long-run or cointegration-based frameworks.

Given that this study adopts a stationary panel framework focusing on short-run and contemporaneous dynamics, the EKC hypothesis is not formally tested. Instead, GDP per capita is included as a linear variable (in first differences), capturing the immediate impact of economic growth on environmental pressure. Therefore, the analysis focuses on short-run linear relationships rather than long-run nonlinear EKC dynamics.

Accordingly, the EKC framework is used as a theoretical reference rather than an empirical specification in this study.

2.2 Economic Complexity and Environmental Sustainability

Economic complexity theory emphasizes the role of productive knowledge, diversification, and technological capabilities in shaping economic outcomes (Hidalgo & Hausmann, 2009). More complex economies are better positioned to adopt cleaner production processes, improve resource efficiency, and promote innovation. As a result, economic complexity can reduce environmental degradation by facilitating structural transformation toward less resource-intensive industries (Chu, 2021; Sbardella et al., 2018).

However, in the short run, increases in economic complexity may also lead to higher environmental pressure due to industrial expansion and increased production activities. This dual effect highlights the importance of considering transitional dynamics in empirical analysis.

2.3 Technology Diffusion and ICT Trade

Technology diffusion plays a critical role in linking economic development to environmental outcomes. Advanced economies act as hubs of innovation, disseminating technologies across countries and sectors (Mealy & Teytelboym, 2020). The ICT trade represents a key channel for this diffusion process.

ICT exports reflect domestic technological advancement and are associated with improved energy efficiency, digital infrastructure, and environmentally sustainable practices (Asongu et al., 2018; Salahuddin & Alam, 2016). Conversely, ICT imports may have ambiguous effects, as they can either facilitate technological upgrading or increase environmental pressure through higher energy consumption and electronic waste generation (Freitag et al., 2021).

2.4 Urbanization and Environmental Pressure

Urbanization and population density are central determinants of ecological footprint dynamics. Higher population concentration increases demand for energy, transportation, housing, and infrastructure, leading to greater environmental pressure (Dietz et al., 2007; York et al., 2003). However, efficient urban planning and sustainable infrastructure can mitigate these effects.

2.5 Conceptual Framework

Combining these theoretical perspectives, the ecological footprint is influenced by economic growth, structural transformation, technological development, and demographic factors. The interaction between these variables determines whether economic expansion leads to environmental degradation or sustainability improvements. This study empirically tests these relationships within a stationary panel framework, focusing on short-run and contemporaneous dynamics.

3 Literature Review

The interplay between economic activities and environmental sustainability has been extensively examined in the empirical literature, particularly in relation to ecological footprint dynamics. The MENA region, characterized by rapid urbanization, economic diversification, and resource-intensive industries, presents unique challenges and opportunities for sustainable development.

Empirical studies highlight the importance of economic complexity in reducing environmental degradation. Sbardella et al. (2018) and Chu (2021) show that more complex economies adopt advanced technologies and transition toward cleaner production systems. In the MENA context, Abid and Gafsi (2025) provide evidence that economic complexity and technological integration enhance environmental sustainability, emphasizing the role of structural transformation.

The role of ICT in environmental sustainability has also been widely documented. Salahuddin and Alam (2016) find that ICT development improves energy efficiency and reduces carbon emissions, while Asongu et al. (2018) demonstrate its contribution to sustainable business models. Evidence from the GCC further confirms that technological progress plays a key role in mitigating environmental pressures (Abid et al., 2024).

Economic growth and urbanization remain major drivers of environmental degradation. The EKC literature suggests that income growth initially increases environmental pressure before leading to improvements at higher income levels (Bretschger, 2015; Dinda, 2004). In urbanized regions such as

MENA, population density exacerbates ecological strain through increased resource demand and waste generation (Ali et al., 2022; Dietz et al., 2007; York et al., 2003).

The environmental effects of FDI and trade are context dependent. Sadorsky (2010) and Borensztein et al. (1998) show that FDI can either increase or reduce environmental degradation depending on regulatory frameworks. Similarly, ICT imports can facilitate technology transfer and energy efficiency improvements when supported by adequate institutional capacity (Kashif et al., 2024; Zhou et al., 2024).

Despite these contributions, the existing literature presents mixed findings, particularly for developing regions such as MENA. Moreover, limited attention has been given to the joint role of economic complexity and ICT trade in shaping ecological footprint dynamics. This study addresses this gap by providing a comprehensive empirical analysis using a consistent econometric framework.

These theoretical foundations provide the basis for the empirical hypotheses tested in this study.

3.1 Study Hypothesis

The ecological footprint measures the environmental impact of human activities, representing the amount of biologically productive land and sea area required to supply the resources consumed and absorb the waste generated by individuals or populations (Global Footprint Network, 2023).

Based on the existing literature and the economic structure of the MENA region, this study proposes a set of hypotheses to examine the relationships between economic, technological, and demographic factors and the ecological footprint within a short-run analytical framework.

Economic complexity is expected to reduce the ecological footprint, as more diversified and knowledge-intensive economies are better positioned to adopt cleaner production technologies and sustainable practices (Hidalgo & Hausmann, 2009; Sbardella et al., 2018), although short-run industrial transitions may temporarily increase environmental pressure.

Similarly, ICT goods exports are anticipated to have a negative effect on the ecological footprint by promoting energy efficiency and enabling digital solutions that support sustainability (Asongu et al., 2018; Salahuddin & Alam, 2016).

In contrast, ICT goods imports are expected to exert an ambiguous impact, as they may either facilitate technological upgrading and efficiency gains or increase environmental pressure through higher energy consumption and electronic waste generation (Freitag et al., 2021).

GDP per capita is hypothesized to positively influence the ecological footprint, reflecting increased consumption and resource use associated with economic growth, consistent with the early stage of the Environmental Kuznets Curve (Bretschger, 2015; Dinda, 2004).

Foreign direct investment (FDI) is also expected to increase environmental pressure, particularly when directed toward resource-intensive sectors, although its impact may vary depending on regulatory frameworks (Borensztein et al., 1998; Sadorsky, 2010).

Finally, population density is expected to exert upward pressure on the ecological footprint due to urbanization-related factors such as increased energy demand, land use, and waste generation (Dietz et al., 2007; York et al., 2003).

4 Methodology

4.1 Econometric models

The econometric models employed in this study aim to analyze the relationships between the ecological footprint and various economic, social, and technological factors in the MENA region using a stationary panel framework. Given the mixed order of integration among variables, the analysis does not rely on cointegration-based techniques. Instead, all non-stationary variables are transformed into first differences to ensure stationarity and avoid spurious regression. To ensure robustness and reliability of the results, multiple models are used, each providing insights into short-run and contemporaneous dynamics of environmental sustainability rather than long-run equilibrium relationships.

The stationary transformation implies that changes in non-stationary variables such as GDP per capita and economic complexity are interpreted as short-run dynamics affecting the contemporaneous level of ecological footprint rather than long-run equilibrium effects. Conceptually, short-run changes in economic activity and structural transformation immediately influence energy demand, production intensity, and resource consumption, which are directly reflected in current environmental pressure. Therefore, the coefficients on differenced variables capture short-run marginal effects of economic and structural changes on the level of ecological footprint rather than long-run elasticities (Cheng et al., 2021; Wong & Yue, 2024).

Consistent with the short-run stationary framework, the empirical models do not include a quadratic GDP term, as the objective is to estimate contemporaneous linear effects rather than long-run nonlinear relationships such as the Environmental Kuznets Curve (EKC), which require different econometric approaches (e.g., cointegration or panel nonlinear models).

Fixed-Effects Model (FEM)

The Fixed-Effects Model (FEM) controls for time-invariant heterogeneity across countries by focusing on within-country variations. Since several variables are non-stationary, the model is estimated using first-differenced variables to ensure stationarity and avoid spurious regression. Therefore, FEM captures short-run dynamics rather than long-run equilibrium relationships. This model is used to examine the short-run effects of economic complexity, ICT exports, GDP per capita, population density, and FDI on the ecological footprint while accounting for individual country characteristics that do not change over time (Baltagi, 2008).

The model is expressed as follows:

$$\mathrm{ECOFP}_{\mathrm{it}} = \alpha_{\mathrm{i}} + \beta_1 \Delta \mathrm{ECI}_{\mathrm{it}} + \beta_2 \Delta \mathrm{ICTE}_{\mathrm{it}} + \beta_3 \mathrm{ICTI}_{\mathrm{it}} + \beta_4 \Delta \mathrm{GDP}_{\mathrm{it}} + \beta_5 \mathrm{FDI}_{\mathrm{it}} + \beta_6 \mathrm{POP}_{\mathrm{it}} + \varepsilon_{\mathrm{it}}, \quad (1)$$

where the differenced variables (ΔECI, ΔICTE, ΔGDP) represent non-stationary series transformed into first differences, while ICTI, FDI, and POP are retained in levels as stationary variables. The term α_i captures unobserved country-specific fixed effects, reflecting time-invariant heterogeneity across countries, while ε_{it} is the idiosyncratic error term.

Random-Effects Model (REM)

The Random-Effects Model (REM) assumes that the individual country effects are random and uncorrelated with the explanatory variables. To maintain econometric validity in the presence of non-stationary variables, REM is also estimated in first differences and therefore reflects short-run relationships. This model combines both within-country and cross-country variations, providing a broader perspective on the short-run influence of the variables on the ecological footprint across the MENA region (Greene, 2003).

$$ECOFP_{it} = \alpha + \beta_1 \Delta ECI_{it} + \beta_2 \Delta ICTE_{it} + \beta_3 ICTI_{it} + \beta_4 \Delta GDP_{it} + \beta_5 FDI_{it} + \beta_6 POP_{it} + u_i + \varepsilon_{it}, \quad (2)$$

where u_i captures unobserved country-specific random effects assumed to be uncorrelated with the explanatory variables, and ε_{it} is the idiosyncratic error term.

This specification ensures consistency between the econometric model and the stationary transformation applied in the empirical estimation.

Pooled OLS Model

The Pooled OLS model assumes that there are no country-specific effects, treating the panel data as if it were a cross-sectional dataset. Given the presence of non-stationary variables, this model is also estimated in first differences and thus captures short-run average effects rather than long-run relationships. This model provides a simple baseline view of the short-run associations between the dependent and independent variables across all countries in the sample (Wooldridge, 2010).

$$\mathrm{ECOFP_{it}} = \alpha + \beta_1 \Delta \mathrm{ECI_{it}} + \beta_2 \Delta \mathrm{ICTE_{it}} + \beta_3 \mathrm{ICTI_{it}} + \beta_4 \Delta \mathrm{GDP_{it}} + \beta_5 \mathrm{FDI_{it}} + \beta_6 \mathrm{POP_{it}} + \varepsilon_{\mathrm{it}}, \quad (3)$$

where the coefficients are interpreted as the average effect of each variable on the ecological footprint, assuming no country-specific differences.

4.2 Unit Root and Cointegration Tests

Before conducting the regression analysis, the stationarity of the panel data series is examined using Fisher-type unit root tests (Choi, 2001; Maddala & Wu, 1999). The results reveal a mixed order of integration across variables. Accordingly, non-stationary variables are transformed into first differences, while stationary variables are retained in levels. This ensures that all estimations are based on stationary series, thereby avoiding spurious regression.

Given this mixed integration structure, the analysis does not rely on cointegration-based approaches. Instead, the empirical models are estimated using stationary transformations, and the results are interpreted as short-run and contemporaneous relationships.

This approach is consistent with recent econometric literature emphasizing the importance of stationarity to avoid misleading inference in panel regressions involving mixed integration orders (Cheng et al., 2021, 2022; Wong & Yue, 2024).

4.3 Dependence and Slope Heterogeneity Tests

To account for potential cross-sectional dependence and heterogeneity in the slopes across countries, the study conducts dependence tests and slope heterogeneity tests. These tests assess whether the relationship between the variables is consistent across all countries or if different countries exhibit unique relationships due to varying economic, social, or environmental conditions (Pesaran, 2006). Cross-sectional dependence may arise when countries in the MENA region are interconnected, and ignoring this could lead to biased estimates (Baltagi et al., 2007).

4.4 Diagnostic Tests

To ensure the validity and reliability of the estimated panel models, a series of diagnostic tests is conducted. First, the Hausman test is applied to determine the appropriate model specification between Fixed-Effects (FE) and Random-Effects (RE) estimators. The null hypothesis of the Hausman test assumes that the random-effects estimator is consistent and efficient, while the alternative hypothesis favors the fixed-effects estimator. The outcome of this test guides the selection of the most suitable model for inference.

In addition, diagnostic tests are performed to detect potential econometric issues in the residuals. Specifically, heteroskedasticity is examined using White's test and the Breusch–Pagan test, while autocorrelation is assessed using the Wooldridge test for serial correlation in panel data (Breusch & Pagan, 1979; Cameron & Trivedi, 2005; White, 1980). These tests help verify whether the residuals satisfy the assumptions of homoskedasticity and independence required for reliable statistical inference.

A formal nonlinearity diagnostic test is conducted to assess whether the linear specification is appropriate and whether the exclusion of a quadratic EKC term is empirically justified. Following Hui et al. (2017), the test examines whether nonlinear dependence remains in the residuals after estimating the linear model. The null hypothesis assumes linearity, while rejection would indicate the presence of a nonlinear structure requiring an alternative specification.

4.5 Robustness check

Finally, model robustness is assessed across FEM, REM, Pooled OLS, and Mixed-Effects GLM models, and the sensitivity of the estimates to alternative specifications is assessed.

We apply the Mixed-Effects Generalized Linear Model (GLM) as an additional econometric technique to validate the results obtained from the baseline panel estimations (FEM, REM, and Pooled OLS). The Mixed-Effects GLM is employed to account for both fixed and random effects in the data, offering flexibility in modeling complex structures where the data may exhibit hierarchical or nested characteristics, such as panel data or repeated observations over time. This method is particularly useful when there are multiple levels of variability, such as individual-specific effects or time-specific variations, that might influence the outcome variable **(**Pinheiro **&** Bates, 2000).

$$\mathrm{ECOFP_{it}} = \alpha + \beta_1 \Delta \mathrm{ECI_{it}} + \beta_2 \Delta \mathrm{ICTE_{it}} + \beta_3 \mathrm{ICTI_{it}} + \beta_4 \Delta \mathrm{GDP_{it}} + \beta_5 \mathrm{FDI_{it}} + \beta_6 \mathrm{POP_{it}} + \mathrm{u_i} + \varepsilon_{\mathrm{it}}, \quad (4)$$

where u_i is the random effect for unit i, capturing the unobserved heterogeneity specific to each unit (e.g., country-specific or region-specific factors influencing ECOFP). $\varepsilon_{\mathrm{it}}$ is the residual error term for unit i at time t, which is assumed to be independent and identically distributed.

By incorporating both fixed and random effects, the Mixed-Effects GLM provides a robust framework for examining short-run variations in the ecological footprint while accounting for hierarchical data structures (Gelman & Hill, 2007; Pinheiro & Bates, 2000).

5 Data

This study utilizes an annual panel dataset on the Ecological Footprint (ECOFP), offering an opportunity to explore the factors driving environmental pressures in the Middle East and North Africa (MENA) region from 1995 to 2023 (Table 1). By analyzing the relationship between the Ecological

Footprint and other economic, social, and demographic variables, the study seeks to provide a deeper understanding of the sustainability of the region's development.

Table 1. Data description

Abbrev.	Indicator Name	Nature	Source
ECOFP	Per capita ecological footprint (in global hectares)	Main (logarithm)	Global Footprint Network (GFN)
ECI	Economic Complexity Index	Main	The Observatory of Economic Complexity (OEC)
ICTE	ICT goods exports (% of total goods exports)	Main	WDI
ICTI	ICT goods imports (% total goods imports)	Main	WDI
GDP	GDP per capita (constant 2015 US$)	Main (logarithm)	WDI
FDI	Foreign direct investment, net inflows (% of GDP)	Control	WDI
POP	Population density (people per sq. km of land area)	Control (logarithm)	WDI

Notes: This table reports the variables used in the analysis, including their abbreviations, definitions, nature of transformation, and data sources. Logarithmic transformations were applied to variables ECOFP, GDP, and POP to stabilize variance and allow interpretation in elasticities. ECOFP = per capita ecological footprint (global hectares), source: Global Footprint Network; ECI = Economic Complexity Index, source: Observatory of Economic Complexity; ICTE = ICT goods exports (% of total goods exports), source: World Development Indicators (WDI); ICTI = ICT goods imports (% of total goods imports), source: WDI; GDP = GDP per capita (constant 2015 US$), source: WDI; FDI = foreign direct investment, net inflows (% of GDP), source: WDI; POP = population density (people per sq. km), source: WDI.

The variables in this analysis provide a comprehensive view of a country's economic and environmental dynamics. ECOFP (Per Capita Ecological Footprint) (measured in global hectares or gha per person) represents the average amount of natural resources and ecosystem services that are required to sustain the lifestyle of an individual in a specific country or region. This measure helps to understand the environmental burden of an individual on the planet's natural resources. ECI (Economic Complexity Index) indicates the sophistication and diversity of a country’s economy, based on the complexity of its exports and industries. ICTE (ICT Goods Exports, % of Total Goods Exports) and ICTI (ICT Goods Imports, % of Total Goods Imports) reflect a country’s involvement in the global ICT sector, showing the share of technology-related products in trade. GDP (GDP per Capita, constant 2015 US$) provides an adjusted measure of a country's economic output per individual, offering insights into prosperity levels. FDI (Foreign Direct Investment, Net Inflows % of GDP) gauges the extent of foreign investments in a country’s economy. Lastly, POP (Population density) measures the number of people living per square kilometer of land area, shedding light on a country’s demographic structure. Together, these indicators help to analyze the relationship between economic development, technological trade, environmental sustainability, and population factors.

Table 2 presents the correlation matrix, which offers valuable insights into the relationships between various variables and the factors influencing the Ecological Footprint (ECOFP). It highlights both the strength and direction of associations between the Ecological Footprint and other economic, social, and demographic indicators.

Table 2. Data characteristics

Variable	ECOFP	ECI	ICTE	ICTI	GDP	FDI	POP
ECOFP	1.0000						
ECI	0.3566	1.0000					
ICTE	-0.0299	0.5283	1.0000				

ICTI	0.2215	0.5232	0.6293	1.0000			
GDP	0.9530	0.4684	0.1186	0.3312	1.0000		
FDI	-0.1429	0.2422	0.2865	0.0808	-0.1187	1.0000	
POP	0.0710	0.4600	0.4226	0.1435	0.0916	0.3057	1.0000

Notes: The table reports pairwise correlation coefficients among the main study variables. Correlations close to ±1 indicate stronger associations. ECOFP = ecological footprint; ECI = economic complexity index; ICTE = ICT goods exports; ICTI = ICT goods imports; GDP = GDP per capita; FDI = foreign direct investment; POP = population density. The correlations provide descriptive insights into potential multicollinearity but do not imply causality.

The Ecological Footprint shows a strong positive correlation with GDP per Capita, indicating that as GDP per capita increases, so does the ecological footprint. This suggests that higher-income countries generally have a larger environmental impact due to increased consumption, industrial activities, and resource usage. This relationship highlights the environmental trade-offs associated with economic growth, where rising prosperity often leads to greater environmental degradation.

Regarding the Economic Complexity Index, there is a moderate positive correlation with ECOFP, implying that more economically complex countries, which typically have diverse and advanced industries, tend to exert greater pressure on the environment. This could be due to the increased use of natural resources required to support these sophisticated industries and the environmental costs of maintaining a diverse export base.

ICT Goods Exports shows a very weak negative correlation with ECOFP, suggesting that the level of ICT goods exports does not have a strong effect on a country's ecological footprint. This could indicate that ICT exports, which often involve less resource-intensive products, do not significantly contribute to environmental degradation compared to other sectors of the economy.

The correlation between ECOFP and ICT Goods Imports is also weak but positive, indicating that the importation of ICT goods has a slight connection with a country's ecological footprint. This may reflect the environmental costs of the global supply chains involved in ICT product manufacturing and transportation, though the impact remains modest.

For Foreign Direct Investment, there is a weak negative correlation with ECOFP, suggesting that foreign investment does not strongly influence a country's ecological footprint. This could be due to the diverse nature of foreign investment, where sectors attracting investment may not always be the most resource-intensive, or the investment may be geared towards more sustainable technologies.

Finally, Population density shows a very weak positive correlation with ECOFP, implying that population density alone does not significantly contribute to the ecological footprint. While more densely populated countries may have greater environmental pressures, other factors, such as consumption patterns and economic activities, are likely more influential drivers of ecological impact.

In summary, ECOFP is most strongly influenced by economic factors such as GDP per capita and economic complexity, reflecting the environmental trade-offs inherent in economic growth and industrial development.

Table 3 summarizes the descriptive statistics of key variables for the MENA region from 1995 to 2023, presenting the number of observations, the mean, standard deviation, and the range (minimum and maximum) for each variable.

Table 3. Descriptive statistics

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
ECOFP	472	1.0900	0.7800	-0.5115	2.7711
ECI	458	-0.3100	0.6800	-3.2298	1.2666
ICTE	334	1.9000	3.2400	0.0000	16.3800
ICTI	343	4.6600	2.8000	0.0000	17.1900
GDP	491	8.9600	1.2100	6.5685	11.3097
FDI	475	1.9200	2.9800	-4.5416	23.5373
POP	475	4.0400	1.2600	1.0256	6.4500

Notes: This table summarizes descriptive statistics for all variables, including the number of observations, mean, standard deviation, and range (minimum–maximum). ECOFP = ecological footprint; ECI = economic complexity index; ICTE = ICT goods exports; ICTI = ICT goods imports; GDP = GDP per capita; FDI = foreign direct investment; POP = population density. Logarithmic transformations are indicated where applied. These statistics highlight the variability and distribution of the data across MENA countries from 1995 to 2023.

The dataset presents a wide range of values across the different variables, highlighting considerable variation in the countries observed. The Ecological Footprint (ECOFP) shows diverse environmental impacts, suggesting that countries have varying levels of resource consumption and waste generation. The Economic Complexity Index (ECI) reflects the differences in the sophistication and diversity of economies, indicating that countries vary significantly in the complexity of their industries and exports.

The share of ICT Goods Exports (ICTE) and ICT Goods Imports (ICTI) in total trade shows a broad disparity, suggesting that some countries are more integrated into the global ICT trade than others. The GDP per Capita (GDP) variable reflects varying levels of economic prosperity, with some countries experiencing much higher income per person than others.

Foreign investment (FDI) also varies significantly across the countries, reflecting differences in how much foreign capital flows into each economy. Population density (POP) shows considerable variation in demographic trends, with some countries having a high concentration of people per square kilometer, while others have lower population density. This variability reflects the diverse geographic and urbanization patterns across the MENA region.

Overall, the dataset highlights the diverse economic, environmental, and demographic profiles of the countries, underscoring the range of experiences and challenges faced by different nations.

6 Results

Table 4 summarizes the results of the Pesaran Scaled LM CD-test for each variable, indicating whether cross-sectional dependence is significant or not. The table also provides the test for slope heterogeneity based on the methodology of Pesaran and Yamagata (2008). This test checks whether the slope coefficients across the panel data are homogeneous, meaning whether the relationship between the dependent variable (Ecological Footprint, or ECOFP) and the independent variables is the same across all units (countries) in the panel.

Table 4. Dependence and slope heterogeneity tests

Pesaran Scaled LM CD-test		**Test for slope heterogeneity**	
Variable	**CD-test Statistic**	**Statistic**	**Value**
ECOFP	8.4960***	Delta	7.0940***
ECI	13.8080***	Adjusted Delta	9.1210***
ICTE	1.2600		

ICTI	2.9360***		
GDP	9.2730***		
FDI	18.0700***		
POP	57.3810***		

Notes: Pesaran's scaled LM CD-test is applied to detect cross-sectional dependence across countries, while Pesaran & Yamagata's test evaluates slope heterogeneity. Both tests include a constant (intercept) without a deterministic trend. The null hypotheses are (i) cross-sectional independence and (ii) slope homogeneity, respectively. Significant results imply interdependence across MENA economies and variation in slope coefficients, justifying the use of heterogeneous panel estimators. ***, **, and * denote significance at the 1%, 5%, and 10% levels.

The Pesaran Scaled LM CD-test results indicate significant cross-sectional dependence for most variables in the MENA region over the study period. Specifically, the Ecological Footprint (ECOFP), Economic Complexity Index (ECI), ICT Goods Imports (ICTI), GDP per Capita (GDP), Foreign Direct Investment (FDI), and Population density (POP) all exhibit significant correlations across countries. This suggests that economic and environmental factors in one country are likely to be influenced by or interconnected with those of neighboring countries. Population density shows a very strong cross-sectional dependence, highlighting the potential regional impact of demographic trends. On the other hand, ICT Goods Exports (ICTE) does not display significant cross-sectional dependence, suggesting that the export of ICT goods is less influenced by trends in neighboring countries.

These findings justify the use of panel estimators that account for cross-sectional dependence and heterogeneity across countries.

The results of the test for slope heterogeneity suggest that the factors influencing the Ecological Footprint (ECOFP) in the MENA region are not the same across all countries, and the relationship between these factors and the Ecological Footprint varies significantly across different panel units.

The results of the Fisher-type unit root tests are reported in **Table 5**. These tests examine the stationarity of the panel series by including an intercept but no deterministic trend in the specification. The findings show that some variables (FDI, POP, and ICTI) are stationary at levels, while ECOFP also appears stationary. However, ECI, ICTE, and GDP are non-stationary in levels but become stationary after first differencing.

Table 5. Unit-root tests

Variable	**Statistic (P)**	**Variable**	**Statistic (P)**
ECOFP	52.4485**	DECOFP	486.4725***
ECI	38.9882	DECI	413.7437***
ICTE	39.1444	DICTE	283.5072***
ICTI	60.6964***	DICTI	355.9857***
GDP	37.5969	DGDP	287.8018***
FDI	125.3317***	DFDI	589.1194***
POP	146.3613***	DPOP	57.6736***

Notes: The Fisher-type panel unit-root test is applied to all variables in levels and first differences. The test specification includes an individual intercept without a deterministic trend, as this setting is most appropriate for macroeconomic variables in panel data. The null hypothesis (H_0) assumes the presence of a unit root, while the alternative (H_1) indicates stationarity in at least one panel series. The results show that some variables (e.g., FDI, POP, ICTI) are stationary in levels, while others (e.g., GDP, ICTE, ECI) become stationary after first differencing. ***, **, and * denote rejection of the null hypothesis at the 1%, 5%, and 10% significance levels, respectively.

These results indicate a mixed order of integration across variables. Accordingly, non-stationary variables are transformed into first differences, while stationary variables are retained in levels. This transformation ensures that all subsequent estimations are based on stationary series, thereby eliminating the risk of spurious regression.

Given this mixed integration structure, the analysis does not rely on cointegration-based approaches. Instead, the empirical models are estimated using stationary panel techniques, and the results are interpreted as short-run and contemporaneous relationships rather than long-run equilibrium effects.

Furthermore, none of the variables is integrated of order two (I(2)), confirming the validity and appropriateness of the adopted stationary panel data framework.

Table 6 reports regression results using FEM, REM, and Pooled OLS estimators. The results from these panel models provide consistent evidence on the determinants of the ecological footprint in the MENA region based on stationary specifications.

Table 6. FEM, REM and OLS Regression models

Dependent Variable: ECOFP (Levels)			
	Fixed Effects Model (FEM)	**Random Effects Model (REM)**	**Pooled OLS**
Variable	**Coefficient**	**Coefficient**	**Coefficient**
DECI	0.1002** (0.0430)	0.0755* (0.0407)	-0.0967*** (0.0286)
DICTE	-0.0126** (0.0057)	-0.0153*** (0.0056)	-0.0371*** (0.0052)
ICTI	-0.0052 (0.0048)	-0.0027 (0.0045)	0.0042 (0.0059)
DGDP	0.4281*** (0.0564)	0.5278*** (0.0382)	0.6396*** (0.0113)
FDI	0.0129*** (0.0028)	0.0123*** (0.0028)	0.0034 (0.0039)
POP	-0.0569 (0.0367)	-0.0419** (0.0305)	0.0489*** (0.0121)
_cons	-2.3930*** (0.5393)	-3.3870*** (0.3846)	-4.7820 (0.1227)
	Model's statistics		
R^2	0.8952	0.9079	0.9337
Adjusted R^2	-	-	0.9325

Notes: The table reports regression estimates from Fixed-Effects Model (FEM), Random-Effects Model (REM), and Pooled OLS. Standard errors are shown in parentheses. ECOFP = ecological footprint; DECI = differenced economic complexity index; DICTE = differenced ICT goods exports; ICTI = ICT goods imports (% of total goods imports); DGDP = differenced GDP per capita; FDI = foreign direct investment, net inflows (% of GDP); POP = population density. The reported coefficients represent short-run marginal effects. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

The Fixed-Effects Model (FEM) results indicate that changes in economic complexity (DECI) are positively associated with changes in the ecological footprint, suggesting that, in the short run, increases in productive sophistication may be accompanied by higher resource use and environmental pressure. ICT exports (DICTE) exhibit a negative and significant effect, indicating that technological advancement contributes to reducing ecological pressure. GDP per capita (DGDP) shows a strong positive effect, confirming that economic expansion is associated with increased environmental strain. Foreign direct investment (FDI) also shows a positive and significant effect, while population density (POP) is not statistically significant in the FEM specification.

The Random-Effects Model (REM) provides similar results. Economic complexity shows a weak positive association with the ecological footprint, while ICT exports continue to reduce environmental pressure. GDP per capita remains a strong positive driver of ecological footprint, reinforcing the link between economic growth and environmental degradation. Population density exhibits a small negative effect, suggesting potential short-run demographic adjustments across countries.

The Pooled OLS model, which provides an overall average relationship across countries, indicates that increases in economic complexity and ICT exports are associated with reductions in the ecological footprint, while GDP per capita significantly increases environmental pressure. These results should be interpreted as short-run average associations across the panel.

Across all panel specifications (FEM, REM, and Pooled OLS), GDP per capita consistently emerges as a key driver of ecological pressure, while ICT exports contribute to reducing environmental impact. Economic complexity shows mixed effects across models, reflecting differences between within-country and cross-country dynamics.

Importantly, these results are interpreted as short-run or contemporaneous relationships, as the estimation strategy is based exclusively on stationary variables and does not rely on cointegration or long-run equilibrium modeling.

Diagnostic Tests

We perform a test for autocorrelation and heteroscedasticity in the residuals to ensure the validity of our results and to validate our model (**Table 7**).

Table 7. Diagnostic test results

Test	**Statistic**	**p-value**
Hausman Test	10.3500	0.1106
White test	0.8000	0.6700
Breusch–Pagan test	1.7900	0.1814
Wooldridge test for autocorrelation	2.7860	0.1101
Hui et al. (2017) nonlinearity test	1.2140	0.2247

Notes: This table reports the results of key diagnostic tests applied to assess the validity and adequacy of the estimated panel models. The Hausman test evaluates the consistency between fixed-effects and random-effects estimators. White and Breusch–Pagan tests are used to detect heteroskedasticity in the residuals, while the Wooldridge test examines the presence of first-order autocorrelation in panel data. In addition, the Hui et al. (2017) nonlinearity test is applied to verify whether the estimated relationships are adequately represented by a linear specification and to assess the empirical validity of excluding a quadratic EKC term. The null hypotheses are: (i) no systematic difference between FE and RE estimators (Hausman), (ii) homoskedastic residuals (White and Breusch–Pagan), (iii) no first-order autocorrelation (Wooldridge), and (iv) linearity of the estimated specification (Hui et al., 2017). Failure to reject the null hypothesis of the nonlinearity test supports the use of the linear short-run stationary panel framework adopted in this study.

The Hausman specification test was conducted to choose between the fixed-effects and random-effects estimators. The test result was statistically insignificant ($\chi^2 = 10.35$, $p = 0.1106$), indicating that the null hypothesis of no systematic difference in coefficients could not be rejected. Therefore, the random-effects model was considered more appropriate and efficient for the analysis. Accordingly, the Random-Effects model is used as the preferred specification, while Fixed-Effects results are retained for robustness

The White test ($p = 0.6700$) and Breusch–Pagan test ($p = 0.1814$) both fail to reject the null hypothesis of homoskedasticity, indicating that there is no evidence of heteroskedasticity in the residuals.

Similarly, the Wooldridge test for autocorrelation (p = 0.1101) does not reject the null hypothesis, suggesting that there is no significant first-order serial correlation in the panel data.

Furthermore, the Hui et al. (2017) nonlinearity test produces a statistically insignificant result (p = 0.2247), implying that the null hypothesis of linearity cannot be rejected. This finding indicates that the relationships among the variables are adequately represented within a linear short-run framework and that there is no strong empirical evidence supporting the inclusion of nonlinear or quadratic specifications such as the EKC term in the current stationary panel setting.

Overall, these diagnostic results confirm that the estimated panel models satisfy the key econometric assumptions, supporting the reliability and robustness of the empirical findings.

Robustness check

We apply the Mixed-Effects Generalized Linear Model (GLM) as an additional econometric technique to verify the robustness of the results and to examine short-run relationships among the variables (Table 8).

Table 8. Mixed-Effects GLM model

Dependent Variable: ECOFP (Levels)	
Variable	**Coefficient**
DECI	-0.0967*** (0.0283)
DICTE	-0.0371*** (0.0052)
ICTI	0.0042 (0.0058)
DGDP	0.6396*** (0.0111)
FDI	0.0034 (0.0039)
POP	0.0489*** (0.0120)
_cons	-4.7820*** (0.1214)

Notes: This table reports estimates from the Mixed-Effects Generalized Linear Model (GLM). Standard errors are reported in parentheses. ECOFP = ecological footprint; DECI = differenced economic complexity index; DICTE = differenced ICT goods exports; ICTI = ICT goods imports (% of total goods imports); DGDP = differenced GDP per capita; FDI = foreign direct investment, net inflows (% of GDP); POP = population density. The estimated coefficients represent average marginal effects. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Consistent with the main panel models, the Mixed-Effects GLM is estimated using stationary variables and therefore captures short-run dynamics.

The results of the Mixed-Effects GLM suggest that several factors significantly influence the ecological footprint. Economic complexity (DECI) and ICT exports (DICTE) are negatively associated with ecological footprint, indicating that improvements in productive sophistication and digital trade can reduce environmental pressure. GDP per capita (DGDP) and population density (POP) show positive and significant effects, reflecting increased environmental pressure from economic and demographic expansion.

The coefficients for ICTI and FDI are not statistically significant, suggesting that these variables do not exert a systematic short-run impact on ecological pressure in the MENA region.

The consistency of results across FEM, REM, Pooled OLS, and Mixed-Effects GLM confirms the robustness of the findings. The analysis demonstrates that the estimated relationships are not driven by spurious correlations, as all models are based on stationary transformations of the data. The consistency of results across different panel estimators further strengthens the robustness of the empirical findings.

Overall, the empirical evidence highlights the importance of economic growth, technological development, and structural transformation in shaping environmental outcomes in the MENA region, within a short-run and contemporaneous analytical framework.

7 Discussion

The empirical results provide important insights into the relationships between economic activities and ecological impacts in the MENA region within a stationary panel framework. Unlike cointegration-based approaches, the findings are interpreted as short-run and contemporaneous relationships derived from estimations using stationary variables.

The coefficient of the Economic Complexity Index (ECI) exhibits mixed effects across model specifications, reflecting differences between within-country dynamics and cross-country variations. More precisely, the estimated coefficient on ΔECI indicates that short-run increases (i.e., changes) in economic complexity can either increase or decrease the ecological footprint, depending on the specification. In some models, increases in economic complexity are associated with higher ecological pressure in the short run, which may reflect transitional phases of industrial expansion and increased resource use. However, in other models, economic complexity contributes to reducing ecological footprint, suggesting that technological upgrading and structural transformation can support environmental sustainability (Chu, 2021; Hartmann et al., 2017; Sbardella et al., 2018; Stojkoski et al., 2022).

The negative and significant coefficient for ICT goods exports indicates that higher ICT exports are consistently associated with reductions in the ecological footprint. More specifically, the coefficient on ΔICTE implies that short-run increases in ICT exports contribute to reducing ecological pressure, reflecting immediate efficiency gains rather than long-run structural effects. This finding suggests that technological advancement and digital trade contribute to improving energy efficiency and promoting cleaner production processes. These results are consistent with previous studies highlighting the role of ICT in enhancing environmental performance through innovation and efficiency gains (Asongu et al., 2018; Freitag et al., 2021; Salahuddin & Alam, 2016).

GDP per capita emerges as a strong and consistent driver of ecological pressure across all model specifications. Importantly, the coefficient on ΔGDP should be interpreted as the effect of economic growth (i.e., short-run changes in income) on ecological footprint, rather than the effect of income levels. The positive relationship indicates that short-run economic expansion is associated with increased consumption, energy use, and resource demand, leading to higher environmental pressure. Thus, the results capture the immediate environmental impact of economic growth dynamics rather than long-run income–environment relationships. This finding is consistent with the early stage of the Environmental Kuznets Curve (EKC), where economic growth is accompanied by environmental degradation and sustainability trade-offs, particularly in resource-dependent economies undergoing structural transformation (Abid, 2025b; Bretschger, 2015; Dinda, 2004).

Population density also shows a generally positive association with ecological footprint in several models. Since POP is included in levels, its coefficient reflects the contemporaneous effect of population concentration on environmental pressure. This result highlights the environmental pressures arising from urbanization, including increased demand for land, infrastructure, and energy. However, the effect is not always statistically significant across all specifications, indicating that demographic impacts may vary depending on country-specific conditions and urban management strategies (Dietz et al., 2007; York et al., 2003).

ICT imports and foreign direct investment (FDI) are found to be statistically insignificant in most specifications. Given that these variables are included in levels, their coefficients capture contemporaneous level effects rather than dynamic changes. This suggests that short-run fluctuations in these variables do not exert a systematic impact on ecological pressure in the MENA region. This result may indicate that the environmental effects of ICT imports and FDI are indirect and depend on complementary factors such as institutional quality, regulatory frameworks, and absorptive capacity (Arif et al., 2021; Borensztein et al., 1998; Sadorsky, 2010).

The insignificant role of FDI suggests that foreign investments in the region are not predominantly directed toward environmentally harmful sectors or that existing regulatory frameworks may mitigate their potential environmental impact. However, it may also reflect a missed opportunity to leverage FDI for promoting green technologies and sustainable development. This highlights the importance of aligning investment policies with environmental objectives to maximize the potential benefits of foreign capital.

Similarly, the limited impact of ICT imports may indicate that the benefits of technology transfer are not fully realized in the absence of adequate infrastructure, human capital, and innovation systems. Previous studies suggest that ICT imports can enhance environmental performance when supported by strong absorptive capacity and effective policy frameworks (Kashif et al., 2024).

Overall, the findings highlight the importance of economic growth, technological development, and structural transformation in shaping environmental outcomes in the MENA region. Crucially, these results reflect short-run marginal effects of changes in key variables rather than long-run equilibrium relationships or level elasticities. The results emphasize that while economic expansion tends to increase environmental pressure in the short run, technological advancement—particularly through ICT exports—can play a mitigating role.

Importantly, these results should be interpreted within a short-run analytical framework, as the estimation strategy does not rely on cointegration or long-run equilibrium relationships. The mixed specification implies that policy conclusions should be drawn in terms of short-run adjustments and dynamic responses rather than structural long-term effects. This distinction is crucial for policy interpretation, as it suggests that immediate policy interventions targeting technological development and efficient resource use can have significant environmental benefits even in the absence of long-run structural adjustments.

8 Conclusion

This study investigates the ecological footprint in the Middle East and North Africa (MENA) region, analyzing its key economic, technological, and demographic drivers over the period 1995–2023. The findings highlight the complex interplay between these variables in shaping environmental sustainability within a short-run and contemporaneous analytical framework based on stationary panel estimations.

The results indicate that ICT goods exports consistently contribute to reducing the ecological footprint, emphasizing the importance of technological advancement and digital trade in promoting environmental sustainability. Economic complexity exhibits mixed effects across model specifications, suggesting that while structural transformation and technological upgrading can support sustainability, short-run increases in productive sophistication may also generate transitional environmental pressures. These findings underline the importance of managing the transition toward knowledge-based economies in a way that balances innovation with environmental protection.

Conversely, GDP per capita emerges as a strong and consistent driver of ecological pressure, indicating that economic growth is associated with increased consumption, energy demand, and resource use. Population density also contributes to environmental strain in several specifications, reflecting the pressures associated with urbanization and demographic concentration. These results highlight the need to carefully balance economic expansion and urban development with sustainability objectives.

ICT imports and foreign direct investment (FDI) are found to have no statistically significant direct impact on the ecological footprint in the short run. However, their potential role in promoting sustainability through technology diffusion and green investment strategies remains important. This suggests that the effectiveness of these channels depends on complementary factors such as institutional quality, regulatory frameworks, and absorptive capacity.

The originality of this study lies in its adoption of a unified stationary panel framework to examine the short-run determinants of ecological footprint in the presence of mixed integration orders, thereby avoiding the limitations of conventional cointegration-based approaches. Unlike previous studies that focus primarily on long-run equilibrium relationships, this research provides novel empirical evidence on contemporaneous dynamics, offering a more accurate representation of short-term environmental responses to economic and technological changes in the MENA region.

Furthermore, this study makes several distinct contributions to the academic literature and policymaking. First, it provides novel empirical evidence on the role of economic complexity and ICT trade as key determinants of ecological footprint in the MENA region, a context that remains relatively underexplored in existing research. Second, it offers a more nuanced analysis by distinguishing between ICT exports and imports, thereby highlighting the asymmetric role of digital transformation in shaping environmental outcomes. Third, from a methodological perspective, the study contributes by adopting a consistent stationary panel framework that avoids reliance on cointegration-based techniques in the presence of mixed integration orders, thereby ensuring robust and reliable inference. Fourth, it bridges the gap between short-run econometric evidence and practical policy design by explicitly linking empirical findings to actionable sustainability strategies.

Overall, the study underscores the importance of integrated strategies that align economic growth, technological development, and environmental policies to achieve sustainable development in the

MENA region. The results suggest that while economic expansion tends to increase environmental pressure in the short run, technological progress—particularly through ICT exports—can play a mitigating role.

From a policy perspective, enhancing economic complexity through investments in innovation, renewable energy, and green technologies is essential. Promoting the ICT sector by expanding digital infrastructure and supporting ICT exports can further contribute to environmental sustainability. In addition, managing urbanization through sustainable planning, green infrastructure, and efficient resource management is crucial to reducing environmental pressures.

Balancing economic growth with sustainability requires the implementation of green growth strategies, including carbon pricing mechanisms, energy efficiency policies, and sustainable water and agricultural management. Encouraging environmentally responsible FDI and improving the capacity to absorb and utilize imported technologies can help transform currently insignificant channels into effective drivers of sustainability. Regional cooperation and knowledge-sharing initiatives can further enhance these efforts.

Finally, public awareness campaigns and capacity-building programs are essential to promote sustainable consumption patterns and integrate environmental considerations into economic decision-making. These strategies can support the transition toward a more resilient and environmentally sustainable development path in the MENA region.

The relationship between economic complexity and environmental outcomes may be bidirectional, as environmental policies can also influence structural transformation. Future research should therefore address potential endogeneity using advanced econometric techniques such as instrumental variables or dynamic panel models (e.g., GMM) to further strengthen the robustness of the findings within a short-run analytical framework.

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