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Assessing the Effects of Economic Structural Changes and Trade Openness on Ecological Sustainability: The Case of the MENA Region

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Abstract

Economic growth driven by unsustainable activities exerts increasing pressure on the environment, resulting in ecological degradation. While research on ecological sustainability in the MENA (Middle East and North Africa) region is expanding, the spatial effects of economic structural changes and trade openness on the ecological footprint remain underexplored. This study addresses this gap by examining whether structural transformations in the economy and trade exert significant spatial direct and spillover effects on the ecological footprint across MENA countries from 2001 to 2021. For this purpose, we used Moran's I test and applied fixed-effect SDM model. To ensure the findings, we checked the robustness of our results across alternative spatial models and other matrices. The results showed that there is significant positive spatial dependence in ecological footprints, indicating that a country's ecological footprint is influenced by those of its neighbors. We find economic structural changes played an important role in reducing the ecological footprints, both directly and through spillover effects. Similarly, trade openness had a significantly negative impact on the ecological footprint; however, the spillover effect was not significant. The results of robustness checks confirmed the environmental impact of structural economic changes and trade openness are robust and not driven by model-specific assumptions. These findings underscore the need for MENA governments to prioritize economic restructuring and promote the adoption of environmentally friendly technologies through strategic trade policies and reduced trade barriers.

Keywords: Ecological footprint, Economic structure, Spatial dependence, Spatial Durbin model, Trade openness.

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Introduction

Environmental degradation—manifested through biodiversity loss, pollution, and land-use change—has became a critical threat to human societies (Keck et al., 2025). Environmental degradation is not merely an ecological concern but a global and multidimensional threat to human well-being and long-term sustainability that directly undermines health, security, and human rights, intensifying existing social inequalities (Banik and Uddin, 2025). Current evidence suggests that the continuation of these trends severely weakens ecosystems' capacity to provide essential services—ranging from climate regulation to food security (Telila et al., 2025).

A key factor behind this trend is extensive economic activities and the continued reliance on conventional energy sources—primarily fossil fuels—to support national economic growth (Zhou et al., 2024). Such growth-oriented strategies have markedly increased ecological footprints across nations and bacome a primary threat to environmental sustainability (International Energy Agency, 2018). These impacts pose significant challenges to sustainable development, particularly in developing countries (Danish and Khan, 2020; Razzaq et al., 2024).

In response to mounting environmental pressures, countries are increasingly adopting comprehensive strategies aimed at balancing economic growth with ecological sustainability. These strategies encompass adjustments across various dimensions, including economic scale, technological innovation, and structural transformation (Li et al., 2021). Among these, scale and technological adjustments are often emphasized due to their immediate and visible impacts. Although slowing economic growth can effectively reduce ecological footprints, such an approach is generally undesirable from a policy perspective (Ahmad et al., 2017). Technological advancements—particularly in energy efficiency—have historically contributed to curbing ecological degradation. However, the potential for further efficiency gains is diminishing, and future technological breakthroughs may yield only marginal improvements (Mi et al., 2015).

As a result, structural changes in both the economy and trade have gained prominence as sustainable and strategic avenues for reducing ecological footprints. These transformations have attracted growing interest from policymakers, especially in developing regions. Notably, the expansion of the tertiary sector and increased trade openness have driven substantial structural shifts in many economies, offering new opportunities to decouple economic growth from environmental harm (Li et al., 2021).

The Middle East and North Africa (MENA) region holds a strategic geographic position at the crossroads of Asia, Africa, and Europe, providing it with significant geopolitical and economic advantages. The region is also endowed with abundant natural resources, including crude oil, natural gas, and various minerals, which have played a vital role in fostering economic development (Doğan et al., 2023; El Khoury et al., 2025). However, following the colonial period, many MENA countries experienced setbacks in their socioeconomic development trajectories (Mrabet et al., 2021). In an effort to accelerate growth and catch up economically, these nations have heavily exploited their natural resources, often at the expense of environmental sustainability (Sun et al., 2022). As illustrated in Figure 1, the ecological footprint across MENA countries has exhibited a consistent upward trend over the two decades leading up to 2021. Notably, six countries in the region—the United Arab Emirates, Qatar, Kuwait, Bahrain, Iran, and Saudi Arabia—rank among the top 20 countries with the highest ecological footprints globally (Global Footprint Network, 2024). In addition to their heavy environmental impact, most MENA nations also contend with severe environmental challenges, including water scarcity, air pollution, and deforestation (Hachaichi and Baouni, 2020). Given the growing severity of environmental degradation, this issue has emerged as a primary policy concern across the region. Consequently, a growing body of environmental economic research (e.g., Al-Mulali and Ozturk, 2015; Guliyev 2024; El Khoury et al., 2025) has focused on investigating the environmental dimensions of economic development. These studies employ various theoretical frameworks and empirical approaches to assess how sustainable development goals can be achieved in the face of persistent environmental challenges.

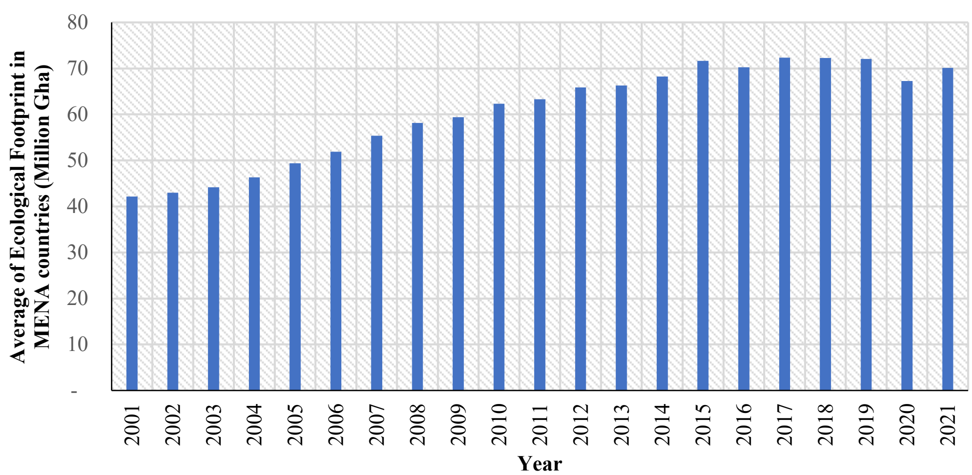

Figure 1- Average of the ecological footprint in the MENA countries (2001-2021) (Global Footprint Network, 2024).

Given the above context, the economic growth of most MENA countries remains heavily reliant on the production and export of oil and gas. However, in light of the global push to reduce environmental pollution and promote sustainability, governments in the region have begun implementing structural reforms in both the economy and trade. These efforts aim to foster economic development while simultaneously improving environmental quality. In this context, understanding the environmental implications of such structural changes is both timely and essential.

Accordingly, this study seeks to answer two main questions. First, what is the effects of economic structural changes and trade openness on the ecological footprint in MENA countries. Second, whether structural changes in neighboring countries exert significant spatial spillover effects on a given country's environmental quality? Our findings not only will make an important contribution to the existing literature by estimating the spatial direct and spillover effects of economic structural changes and trade openness on the ecological footprint, but also, refine the main axes to enhance the environmental quality without delimiting or stopping economic growth. By doing so, it offers novel insights into the environmental implications of structural transformations in the MENA region—an area that has been underexplored in prior research. Additionally, the findings have important policy relevance, providing evidence-based guidance for designing effective strategies to enhance ecological sustainability.

A review of the existing literature reveals a significant gap concerning our research objectives. While numerous studies have explored the environmental impacts of various economic indicators—such as economic growth, economic complexity, and financial development (Nathaniel et al., 2020; Saud et al., 2023; Alofaysan, 2024; El Khoury et al., 2025)—none, to the best of our knowledge, have specifically examined the effects of structural changes in the economy, particularly through the expansion of the services sector, on ecological sustainability in the MENA region. Moreover, prior studies have consistently shown that industrialization significantly contributes to the rise in ecological footprints (Ragmoun, 2023; El Khoury et al., 2025). However, the potential mitigating role of structural shifts away from industry toward services remains underexplored, highlighting a critical gap that this study aims to address. Recent advances in artificial intelligence (AI) and digital technologies further reinforce this gap, as emerging evidence shows that AI-driven innovation substantially improves environmental efficiency across countries (Zhang et al., 2025) and plays a growing role in shaping sustainability outcomes. Therefore, investigating the effects of economic structural changes is essential for informed policymaking aimed at environmental sustainability. Among the three major sectors, the tertiary industry is generally associated with cleaner production processes and lower levels of environmental pollution compared to the primary and secondary sectors (Touati & Ben-Salha, 2024). Moreover, studies have shown that AI adoption is more prevalent within service-oriented sectors, and this technological diffusion contributes to enhanced environmental sustainability, partly through improved energy efficiency and alignment with SDGs related to clean energy and climate action (Wang et al., 2025a). In this context, Li et al. (2021) demonstrated that economic structural changes—measured by the share of the tertiary sector in total employment—play a significant role in mitigating environmental pollution. Complementing this view, Wang et al. (2025b) showed that artificial intelligence significantly enhances corporate sustainability performance, particularly within service-dominated and transitioning economies, suggesting that technology-driven structural transformation can reinforce environmental gains. This suggests the continued development of the tertiary industry can contribute positively to environmental sustainability. Despite this, no existing studies have examined the spatial direct and spillover effects of economic structural changes on the ecological footprint within the MENA region. This spatial dimension is particularly important in regions with close economic and geographic linkages, such as MENA, where policies and economic transformations in one country may have cross-border environmental implications. Although Ramezani et al. (2022) applied a Spatial Durbin Model (SDM) and incorporated variables such as per capita income to analyze environmental pressures in MENA countries, their study did not account for structural economic changes. A dedicated discussion of prior spatial studies is therefore essential. Ramezani et al. (2022) demonstrated significant spatial dependence in ecological footprint patterns across MENA countries, providing a strong justification for our use of the SDM framework. Our analysis extends their work by incorporating structural economic variables—especially the shift toward the tertiary sector—that were not included in their model, thereby adding an important new dimension to understanding spatial environmental dynamics in the region. Therefore, we need for a more comprehensive spatial analysis that explicitly considers how economic restructuring may influence both direct and spillover ecological impacts across the region. This need is further emphasized by recent findings showing that financial development and AI together facilitate cleaner energy transitions (Wang et al., 2026), reinforcing the importance of technology-linked structural change in shaping environmental outcomes.

Furthermore, international trade plays a pivotal role in enhancing environmental quality through the diffusion of technology. Countries with more open trade structures are better positioned to import environmentally friendly and cleaner technologies from developed economies, thus reducing their ecological footprint. However, emerging research also warns that global sustainability dynamics are increasingly shaped by deglobalization pressures, which can influence the ecological footprint through changes in human development pathways and international integration (Wang et al., 2025c). However, trade openness does not universally lead to improved ecological sustainability. Through the scale and composition effects, increased production and exports—often pursued for economic gain—can intensify pressure on natural and ecological resources (Aminizadeh et al., 2024). Additionally, developed countries with stringent environmental regulations may relocate pollution-intensive industries to developing nations with weaker standards, a phenomenon often referred to as the “pollution haven” hypothesis (Schneiter and Mellon-Bedi, 2025). The existing literature on trade in the MENA region remains limited and lacks consensus. For example, Al-Mulali and Ozturk (2015) found that trade openness significantly increases the ecological footprint in MENA countries, suggesting a negative environmental impact. In contrast, Mrabet et al. (2021) reported that trade openness contributes to reducing the ecological footprint, thus enhancing ecological quality. To situate the MENA region in the global context, it is important to note that Zambrano-Monserrate et al. (2020) identified strong global spatial dependence in ecological footprints and highlighted biocapacity and trade as key interconnected drivers of spatial environmental dynamics. Engaging with their global findings strengthens the methodological justification for our use of a spatial econometric approach and provides an essential benchmark against which the MENA-specific patterns can be interpreted. Their results also indicate that trade-related spillovers can be substantial at the international level, raising questions about whether the absence of spillover effects reported by Ramezani et al. (2022) reflects regional particularities or model limitations—an issue our study directly revisits. Regarding spatial effects, Ramezani et al. (2022) showed that while trade openness exhibits significant spatial direct effects on the ecological footprint, its spatial indirect effects are statistically insignificant, implying that trade liberalization in neighboring countries do not significantly influence a given country's environmental outcomes. Nevertheless, findings from other regional studies like Zambrano-Monserrate et al. (2020) have highlighted significant spatial indirect effects of trade openness via the Spatial Durbin Model, casting doubt on the conclusions of Ramezani et al. (2022). Given these mixed results, a comprehensive investigation into both the spatial direct and spillover effects of trade openness on ecological sustainability in the MENA region is both timely and necessary.

In sum, To strengthen the conceptual clarity of the study, it is important to explicitly outline the proposed relationships among the main indepenedet variables and ecologica footprint. According to the literature gaps in the MENA region, this study examins two main hypothesis:

H1: Economic structural changes has a negative and significant direct spatial and spillover effects on the ecological footprint. This implies that a shift toward more efficient and service-oriented economic structures reduces environmental pressure both within a country and across its neighboring countries.

H2: Trade openness has a negative and significant direct spatial and spillover effects on the ecological footprint. In other words, higher levels of trade openness lower a country's ecological footprint while simultaneously reducing environmental pressure in adjacent countries through spatial transmission channels.

Materials and methods

Research model

This study aims to analyze the spatial effects of economic structural changes and trade openness on the ecological footprint in the MENA countries. Our empirical model to achieve the research purpose is as follows:

$$LnEFC_{it} = \beta_0 + \beta_1 LnGDP_{it} + \beta_2 LnGDP_{it}^2 + \beta_3 LnBIO_{it} + \beta_4 LnECS_{it} + \beta_5 LnTRA_{it} + \beta_6 LnREN_{it} + \beta_7 LnURB_{it} + u_{it} \quad (1)$$

where, *i* denotes country and *t* shows year. EFC denotes the ecological footprint. GDP and GDP^2 show GDP per capita (in US$ at constant 2015 prices), and the squared GDP per capita, respectively. Most studies support the EKC hypothesis for the MENA countries (Nathaniel et al., 2020; Touati and Ben-Salha, 2024). However, the study by El Khoury et al. (2025) did not confirm the EKC hypothesis. Therefore, this study anticipates the ecological footprint will be positively influenced by income ($\frac{\partial EFC_{it}}{\partial GDP_{it}} > 0$), and negatively influenced by squared income ($\frac{\partial EFC_{it}}{\partial GDP_{it}^2} < 0$), showing that the ecological footprint begin to decrease after a certain level of income. BIO denotes biocapacity. Relevant studies implied that biocapacity increases the ecological footprint (Zambrano-Monserrate et al., 2020). By contrast, Jabeen et al. (2023) revealed the negative relationship between biocapacity and the ecological footprint for BRI economies. Therefore, biocapacity can either to increase and decrease the ecological footprint ($\frac{\partial EFC_{it}}{\partial BIO_{it}} > 0\ or < 0$).

ECS denotes the economic structure. Following Li et al. (2021), the ratio of employment in service sector is defined as a proxy of economic structure. Considering that tertiary industry causes less environmental damage compared to primary and secondary industries (Abdulmagid Basheer Agila et al., 2022; Li et al., 2024), this study theorizes the negative effects of economic structure on the ecological footprint ($\frac{\partial EFC_{it}}{\partial ECS_{it}} < 0$). TRA reveals the trade openness. Previous studies determined the influence of trade openness on the ecological footprint and showed the mixed findings, like negative influence (Liu et al., 2022; Mrabet et al., 2021), and positive influence (Al-Mulali and Ozturk, 2015; Ramezani et al., 2022). Therefore, trade openness is expected to decrease or increase the ecological footprint ($\frac{\partial EFC_{it}}{\partial TRA_{it}} < 0\ or > 0$).

REN denotes renewable energy consumption. Most empirical research (e.g., Li et al., 2023; Alofaysan, 2024; El Khoury et al., 2025) showed that renewable energy consumption reduces the environmental degradation. Thus, renewable energy consumption is expected to have a negative effect on the ecological footprint ($\frac{\partial EFC_{it}}{\partial ENS_{it}} < 0$). URB reveals urbanization. Although most research showed the positive effects of urban population on the ecological footprint (Ragmoun, 2023; El Khoury et al., 2025), the study by Khalfaoui et al. (2023) found a negative effect. Therefore, urbanization is expected to have a positive or negative effect on the ecological footprint ($\frac{\partial EFC_{it}}{\partial URB_{it}} > 0\ or < 0$).

Econometrics method

This research applies spatial econometric methods to determine the spatial direct and spillover effects of economic structural changes and trade openness on the ecological footprint for 17 MENA countries in 2001-2022. Spatial econometric modelling is applied to capture the environmental interlinkages that arise when ecological pressures or policy actions in neighbouring countries affect local country. These models mitigate omitted-variable bias arising from ignoring geographic interlinkages and provide richer policy-relevant insights compared with standard panel techniques (LeSage & Pace, 2009; Elhorst, 2014). For these davantages, most environmetal economic studies were extensively used the spatial econometrics method (Abban et al., 2025; Fan et al., 2026; Sunge and Espoir, 2026). However, a key methodological consideration is the specification of the spatial weight matrix, as different matrix structures may alter the detected intensity and direction of environmental spillovers. For this reason, most empirical studies (eg., Aminizadeh et al., 2024; Sunge and Espoir, 2026). were used test and erro test method for identifying best spatial weight matrix and conducted robustness check according other matrices.

Spatial autocorrelation test

The Moran's I index is widely used to determine the spatial dependence in empirical studies (Zambrano-Monserrate et al., 2020). The Moran’s I is shown as follows:

$$Moran's\ I = \frac{n}{\sum_{i=1}^{n}(x_i - \bar{x})} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{2}$$

Zero score shows no spatial dependence. The positive Moran’s I score shows positive spatial correlation, whereas, the negative Moran’s I score indicates negative spatial correlation.

Spatial econometrics models

By adding the geographical information of the MENA countries to ordinary models generates spatial econometrics models, which can explain the spatial dependence of the ecological footprint between countries. The main models to determine the spatial effects are the spatial Durbin model (SDM), the spatial autocorrelation model (SAC), the spatial lag model (SLM), and the spatial error model (SEM). Since SDM contains both the spatially lagged dependent and independent variables, this model is extensively used in empirical studies as a comprehensive spatial model (Ragmoun, 2023; Abban et al., 2025). Considering the significant effect of spatially lagged independent variables on the dependent variable, omitting these effects can lead to bias in estimation (Elhorst, 2014). SDM is as follows (LeSage and Pace, 2009):

$$Y = \rho WY + \beta X + \theta WX + \varepsilon \tag{3}$$

where Y is dependent variables and X denotes independent variables. WY is spatially lagged dependent variable, and W is the non-negative spatial weight matrix. This study chooses the three nearest neighbors spatial weights matrix (W_k3) based on the test and error method. ρ is spatial autoregressive parameter. If it is statistically significant, it shows the ecological footprint in a country is significantly affected by the ecological footprint in neighboring countries. β indicates the effects of the independent variables on the dependent variable. WX is spatially lagged independent variables, and θ demonstrates the effects of the spatially lagged independent variables on the dependent variable. ε is the error term.

According to the LeSage and Pace (2009), we use the decomposition method to estimate the direct and indirect effects to increase the credibility of the research results, because the interpretation of the estimated coefficients leads to erroneous conclusions. Hence, to, this study uses. The SDM model is rewritten in vector form, which is shown in equation (4):

$$Y_{it} = (I - \rho W)^{-1}(\beta X + \theta WX) + (I - \rho W)^{-1}(\varepsilon) \quad (4)$$

where "I" shows an identify matrix. Other variables and parameters are defined in equation (3). The direct effect is the average of matrix diagonal elements, and the spillover effect is the average of row sums of matrix non-diagonal elements. The total effect is sum of the direct and spillover effects (LeSage and Pace, 2009).

Data

This study determines the spatial direct and indirect effects of economic structure and trade openness on the ecological footprint using balanced panel data for selected MENA countries during 2001-2021. The choice of time series length and sample countries is determined by data availability on the ecological footprint and independent variables. Data for the ecological footprint and biocapacity are obtained from the Global Footprint Network database (Global Footprint Network, 2024). GDP per capita is measured as constant 2015 US$. Economic structure is the employment ratio in service sector. Trade openness is the sum of exports and imports of goods and services measured as a share of GDP. Renewable energy consumption is the share of renewable energy in total final energy consumption. Urbanization is the share of people living in urban areas in total population. Data for GDP per capita, economic structure, trade openness, renewable energy consumption, and urban population are collected from the World Development Indicators database (World Bank, 2024). The study variables are converted to logarithmic form. In panel-data econometric modelling, log transformations are widely employed because they reduce heteroskedasticity, and allow coefficients to be interpreted in elasticity form. These advantages contribute to more robust estimation and more meaningful comparisons across units and periods (Greene, 2003; Wooldridge, 2010). Table 1 shows the descriptive statistics of the study variables and source of data.

Table 1. Descriptive statistics of the variables, and source of data.

Variable	Mean	Std. dev.	Min	Max	Expected Sign	Source
LnEFC	1.269	0.741	0.065	2.771		Global Footprint Network (GFN)
LnGDP	9.129	1.136	6.613	11.205	+	World Bank
LnBIO	-0.449	0.596	-1.529	1.309	+/-	Global Footprint Network (GFN)
LnECS	4.095	0.203	3.547	4.422	-	World Bank
LnTRA	4.374	0.376	3.396	5.257	+/-	World Bank
LnREN	-1.246	3.512	-6.908	3.109	-	World Bank
LnURB	4.319	0.221	3.754	4.605	+/-	World Bank

Results and discussion

In the first step, we tested the cross-sectional dependence and the results are presented in Table 2. According to the results of Pesaran (2004) test, cross-sectional dependence exists between countries. However, the results of Pesaran and Xie (2021) and Juodis and Reese (2021) tests revealed that there is weak cross-sectional dependence. Therefore, spatial econometrics models is an appropritae method to consider the dependence between countires (Algeri et al., 2022). The results of multicollinearity test using Variance Inflation Factors (VIF) and first- and second-generation unit root tests are presented in Table 3. There is no issue of multicollinearity, because the obtained values are less than 5. The unit root tests results showed the null hypothesis is rejected at 5 percent level and hence, all study variables are stationary.

Table 2. The results of croos-sectional dependence (CSD) tests.

Test	Pesaran (2004)	Pesaran and Xie (2021)	Juodis and Reese (2022)
CSD	4.35	0.40	-0.49
(p-value)	(0.000)	(0.623)	(0.692)

Source: Research findings.

Table 3. The results of multicollinearity and first- and second-generation unit root tests using Fisher-ADF and CADF test.

Variable	Multicollinearity test	First-generation unit root test	Second-generation unit root test
	VIF	Fisher-ADF	CADF
LnEFC		-6.761***	-1.686**
LnGDP	3.33	-6.041***	-1.664**
LnBIO	2.22	-7.986***	-2.479***
LnECS	2.37	-5.771***	-3.237***
LnTRA	1.43	-6.868***	-2.979***
LnREN	2.24	-4.825***	-2.804***
LnURB	3.59	-9.491***	-1.937***
Mean VIF	2.53		

** p-value<0.05, *** p-value<0.01.
Source: Research findings.

The Moran's I results are shown in Table 4. Moran's I values for the ecological footprint are positive and statistically significant at 1 percent level, revealing that there exists spatial dependence between countries in the MENA region. Our finding consistent the results of previous studies (Ramezani et al., 2022; Ragmoun, 2023), which showed the ecological footprint in local country in the MENA region is influenced by the ecological footprint in other countries.

Table 4. The results of Moran's I index.

Year	Moran's I	p-value	Year	Moran's I	p-value
2001	0.367	**0.000**	2012	0.395	**0.000**
2002	0.411	**0.000**	2013	0.321	**0.000**
2003	0.473	**0.000**	2014	0.508	**0.000**
2004	0.426	**0.000**	2015	0.504	**0.000**
2005	0.467	**0.000**	2016	0.477	**0.000**
2006	0.460	**0.000**	2017	0.483	**0.000**
2007	0.510	**0.000**	2018	0.468	**0.000**
2008	0.533	**0.000**	2019	0.500	**0.000**
2009	0.513	**0.000**	2020	0.447	**0.000**
2010	0.545	**0.000**	2021	0.343	**0.000**
2011	0.518	**0.000**	mean	0.489	**0.000**

Source: Research findings.

Table 5 presents the findings of SLM, SEM, SAC and SDM models. We used the suggested procedures by Belotti et al. (2017) to identify the best spatial model,. The SDM model would not be simplified to the SLM and SEM, according to the results of LR-test. Additionally, Accroding to the AIC and BIC results for the the SDM and SAC models, we found SDM is the best model to examine the research purpose. Similarly, literature review (e.g., Ali et al., 2024; Sunge and Espoir, 2026) confirms SDM is efficient compared to other spatial models. The results demonstrate that the spatial coefficient (rho) is positive and significant. This finding shows that ignoring the spatial effect would lead to inconsistent and biased results (Aminizadeh et al., 2024). Table 6 shows the results of cross-sectional dependence for SDM residual. The CD test findings reveal cross-sectional independence and confirm the SDM results are unbiased.

Table 5. The results of spatial econometrics models.

Variable	SLM		SEM		SAC		SDM	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
lnGDP	0.924	**0.001**	0.870	**0.002**	0.987	**0.000**	0.818	**0.003**
lnGDP2	-0.032	**0.039**	-0.031	**0.045**	-0.034	**0.020**	-0.023	0.132
lnBIO	0.140	**0.000**	0.163	**0.000**	0.132	**0.000**	0.195	**0.000**
lnECS	-0.648	**0.000**	-0.578	**0.000**	-0.656	**0.000**	-0.550	**0.000**
lnTRA	-0.090	**0.005**	-0.068	**0.048**	-0.098	**0.001**	-0.133	**0.000**
lnREN	-0.017	**0.008**	-0.018	**0.006**	-0.014	**0.026**	-0.016	**0.011**
lnURB	0.800	**0.000**	0.778	**0.000**	0.796	**0.000**	0.931	**0.000**
WlnGDP							1.433	**0.001**
WlnGDP2							-0.068	**0.005**
WlnBIO							0.005	0.944
WlnECS							-0.397	**0.051**
WlnTRA							0.006	0.907
WlnREN							0.000	0.988
WlnURB							0.017	0.973
Rho	0.284	**0.000**			0.432	**0.000**	0.128	**0.052**
Lambda			0.249	**0.000**	-0.345	**0.005**		
sigma2_e	0.011	**0.000**	0.011	**0.000**	0.010	**0.000**	0.010	**0.000**
SDM-SLM							26.620	**0.000**
SDM-SEM							44.060	**0.000**
Hausman test							262.80	**0.000**
AIC	-578.286		-562.445		-583.259		-590.604	
BIC	-543.386		-527.545		-544.481		-528.560	
R-squared	0.870		0.870		0.846		0.865	

Source: Research findings.

Table 6. The results of cross-sectional dependence for SDM residual.

Test	Pesaran CD (2004)
CD	-1.45 (0.148)

Source: Research findings.

Table 7 shows the results of direct, indirect, and total effects of SDM model. This research shows the expected positive spatial direct and indirect effects of GDP per capita on the ecological footprint in the MENA countries, meaning that economic growth in a country leads to environmental degradation in own country and neighboring countries. This finding is similar with the results of previous studies (Nathaniel et al., 2020; Touati and Ben-Salha, 2024). However, the spatial effect of GDP per capita squared on the ecological footprint is negative and significant, confirming the EKC hypothesis for the MENA countries. This indicates that nations after the initial level of economic growth realize the importance of the environment in human well-being and begin to care about the ecological sustainability. This is consistent with the results previous studies (Saud et al., 2023; Touati and Ben-Salha, 2024), which showed the inverted U-shaped EKC between income and ecological footprint in the MENA region. Conversely, some research, like El

Khoury et al. (2025) revealed that the inverted U-shaped EKC is not validated. In addition, we find there is EKC relationship between neighboring countries' income and local countries' ecological footprint, meaning that income growth in neighboring economies improves a nation's environmental quality through channels such as technology diffusion, shared regulatory practices, and cross-border environmental externalities (Abban et al., 2025). These positive spillovers enlarge the total marginal effect of income on environmental outcomes and imply that regional economic upgrading accelerates the improving ecological sustainability. These findings align with recent spatial-EKC research emphasizing the importance of regional interdependencies in shaping environmental performance (Aminizadeh et al., 2024; Schneiter and Mellon-Bedi, 2025).

It is worth nothing that the estimated Turning Point of the EKC—approximately 222,000 USD of per-capita income—lies far beyond the current and foreseeable income levels of economies in the region. This shows that relying solely on economic growth to eventually reverse environmental degradation can be unrealistic under existing development trajectories. Therefore, the EKC relationship should be interpreted with caution, as the income-driven turning predicted by the model is unlikely to materialize in practice. Policymakers in the region therefore need to prioritize direct environmental interventions and economic structural reforms, rather than assuming that rising income alone will naturally lead to improved environmental outcomes. Recent empirical research shows that the EKC Turning Point often lies at unrealistically high-income levels, challenging the idea that growth alone will reduce pollution. Therefore, most developing economies cannot reach the income threshold needed for EKC-based environmental improvement (Durmaz and Thompson, 2024).

Our findings show that there is significant and positive relationship between biocapacity and ecological footprint. This means economies with higher biocapacity are tempted to consume more environmental resources to achieve economic goals, leading to loss of biodiversity and ecological degradation. MENA countries as resource-dependent economies often prioritize economic growth over environmental sustainability. In the last two decades, there has been a lot of competition between oil-exporting countries because of rising oil prices, which has resulted in excessive use of biocapacity without considering their destructive effects on the environment. For this reason, a number of MENA countries like Saudi Arabia and United Araba Emirates are among the top 10 polluters. Weak governance is a main reason to exacerbate degradation due to weak implementation and enforcement of environmental laws and policies and limited public accountability (Akpan and Kama, 2023; Saba et al., 2025). Bilgili et al. (2023) stated that the reliance on resource rents and fossil fuels weakens institutional incentives to prioritize environmental sustainability. In this regard, Akpan and Kama (2023) showed that strong governance significantly increases environmental sustainability, particularly by limiting fossil fuel use. This result is consistent to the previous research (Zambrano-Monserrate et al., 2020; Kassouri and Altıntaş, 2020), which found a positive and significant relationship between the biological capacity and the ecological footprint. However, Jabeen et al. (2023) showed a significant negative effect of biocapacity on the ecological footprint in Belt and Road Initiative countries.

Table 7. The results of direct, indirect and total effects of SDM.

Variable	Direct effect		Indirect effect		Total effect	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
lnGDP	0.874	**0.002**	1.687	**0.000**	2.561	**0.000**
lnGDP2	-0.026	0.104	-0.078	**0.002**	-0.104	**0.001**
lnBIO	0.201	**0.000**	0.031	0.651	0.232	**0.001**
lnECS	-0.565	**0.000**	-0.527	**0.013**	-1.092	**0.000**
lnTRA	-0.134	**0.000**	-0.009	0.874	-0.143	**0.025**
lnREN	-0.017	**0.009**	-0.001	0.922	-0.018	0.195
lnURB	0.943	**0.000**	0.151	0.753	1.095	**0.043**

Source: Research findings.

Our results show that the economic structure has negative and significant spatial direct, spillover and total effects on ecological footprint in the MENA countries. This means increase in proportion of service sector leads to reduce the environmental degradation. A 1% increase in the proportion of service sector decreases 1.092% ecological footprint. The economic structure dominated by the tertiary industry gradually forms by increasing the proportion of employed people in the service industry and the economic structure dominated by the secondary industry begins to weaken. Therefore, since the tertiary industry is generally associated with cleaner production processes and lower levels of environmental pollution, the demand for natural and environmental resources will be reduced. This finding shows ecological sustainability can be achieved by optimal allocating the resources and adjusting industrial structure. In terms of the spatial spillover effects, ecological footprint in a country is negatively impacted by economic structure in neighboring countries, highlighting that service-oriented transformation in neighboring economies contributes to local country's environmental improvement, likely through channels such as reduced resource intensity and diffusion of cleaner technologies. This finding implies that regional structural upgrading can mitigate cross-border environmental pressures and confirms the importance of aligning national environmental policies with broader regional development strategies to fully realize the beneficial spillover effects associated with service-driven economic change (Opoku-Mensah, 2023; Abban et al., 2025). The study by Li et al. (2021) showed that development of service sector plays an important role in reducing environmental pollution at global level. Moreover, Abdulmagid Basheer Agila et al. (2022) found that improvements in the economic structure could contribute to improve the environmental quality. In line with this, the studies by Al-Mulali and Ozturk (2015) and Ragmoun (2023) were found the significant effect of industrialization in increasing MENA countries' ecological footprint. However, El Khoury et al. (2025) do not show the significantly negative effect of service sector on the ecological footprint. Moreover, Destek (2021) revealed that although industrialization and reindustrialization increase the environmental degradation, reindustrialization because of technology advancement has lower adverse impact on the environmental and ecological sustainability.

Trade openness significantly reduces the ecological footprint in the MENA countries. A 1% increase in trade openness leads to 0.143% decrease in the environmental degradation. Importing new clean technologies and replacing them with old technologies is a solution to environmental problems. Therefore, international trade can improve environmental sustainability by transferring new clean and environment friendly technologies. In this regard, Saghaian et al. (2020) found that trade openness has significantly positive effect on climate-smart goods trade in the MENA region. Mrabet et al. (2021) revealed that trade liberalization significantly reduces MENA region's ecological footprint. By contrast, Jabeen et al. (2023) stated that greater trade puts more pressures on the environment. Zambrano-Monserrate et al. (2020) found the significant positive effect of openness on the ecological footprint. We found that the spatial spillover effect of trade openness is not statistically significant, meaning that trade openness in neighboring countries has no significant effects on the ecological footprint in local country. This finding shows the structural and institutional characteristics of MENA economies. Most countries continue to rely on oil rents and exhibit limited industrial diversification, conditions that restrict the cross-border diffusion of cleaner technologies even when trade openness expands (Beck & Richter, 2021). Weak intra-regional economic integration, shallow participation in shared value chains and fragmented technology-transfer channels reduce the likelihood that trade reforms in one country generate significant environmental improvements in neighboring countries (Ahmed, 2025). In addition, domestic factors such as dependence on fossil-fuel rents and constrained regulatory capacity dominate environmental outcomes, thereby overshadowing potential spatial spillovers from trade openness (Al-Saffar, 2025). This result is consistent to the results of Ramezani et al. (2022), which showed that trade openness in neighboring countries has no significant effect on local country's ecological quality in the MENA region.

Renewable energy consumption has a significantly negative spatial direct effect on ecological footprint, meaning that reduction in environmental degradation in a local country is significantly affected by its increasing consumption of renewable energy. This finding is similar to the previous studies (Alofaysan, 2024; El Khoury et al., 2025), which showed the significant effect of the renewable energy consumption on the ecological footprint in the MENA region. However, the spatial spillover effect of renewable energy consumption is not significant, meaning that there is no relationship between renewable energy consumption in neighboring countries and local country's ecological footprint. This may reflect the limited share of renewable energies in regional energy systems, which reduces cross-border influence (Abban et al., 2025). In addition, weak grid interconnections and low levels of energy-market integration in many MENA economies restrict the physical and economic transmission of renewable-energy gains across borders. This effect is further muted by policy and technological misalignment among economies, as well as the dominance of more powerful structural drivers such as institutional quality and fossil-fuel dependence that overshadow the relatively small potential spillovers from renewable energies (Abban et al., 2025; Stiewe et al., 2025). Our finding contradicts the result by Ragmoun (2023), who found that the ecological footprint in local country was negatively influenced by the consumption of renewable energy in other countries.

Urbanization has significantly positive spatial direct and total effects on ecological footprint. This shows the development of urban population increases the environmental degradation. Similar findings were observed in the MENA countries. For instance, Al-Mulali and Ozturk (2015) showed that increase in urbanization led to increase the ecological footprint in the MENA region. Touati and Ben-Salha (2024) stated that the rapid urbanization in the MENA countries had a harmful effect on the ecological sustainability. The insignificant spatial spillover effect of urbanization reflects the fact that urbanization largely affects local country's environmental quality. Because urban systems in the region also lack spatial and institutional integration, growth in urban population in neighboring nations does not directly influence resource use or pollution levels in local nation. Consequently, stronger structural determinants such as economic structure and economic growth tend to overshadow any limited spillover effects associated with social factors like urbanization.

Robustness check

To ensure the robustness of the empirical findings, several complementary spatial specifications were estimated in addition to the baseline static Spatial Durbin Model. First, alternative spatial models including SLM and SAC were employed, and the results consistently confirmed the significance and direction of the main independent variables, particularly the role of structural economic changes (Table 8). Second, spatial weight matrices of four nearest neighbors (Wk_4) and inverse-distance (W_i) were tested to assess sensitivity to spatial dependence assumptions, and the core coefficients remained stable across these specifications (Table 9). Third, a dynamic SDM was estimated to account for temporal persistence in environmental indicators, yielding results broadly consistent with the static framework (Table 10). Finally, the dependent variable was replaced by CO_2 emissions instead of ecological footprint, and the most results again remained unchanged (Table 11). Consequently, these robustness checks demonstrate that the main empirical relationships are not sensitive to alternative modelling choices. The central conclusion-that structural economic transformation toward services contributes to environmental improvement-remains stable across other models, dynamic SDM, different spatial weight matrices, and alternative dependent variable. This convergence across specifications confirms that the environmental implications of target variables-particularly those arising from structural economic changes- are robust and not dependent on model-specific assumptions.

Table 8. The results of direct, indirect and total effects across alternative models.

Variable	Direct effect		Indirect effect		Total effect	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
Fixed-effect SLM model						
lnGDP	1.029	**0.000**	0.446	**0.017**	1.474	**0.000**
lnGDP2	-0.038	**0.018**	-0.017	**0.059**	-0.055	**0.019**
lnBIO	0.179	**0.000**	0.078	**0.006**	0.257	**0.000**
lnECS	-0.606	**0.000**	-0.268	**0.011**	-0.875	**0.000**
lnTRA	-0.077	**0.027**	-0.035	0.111	-0.112	**0.040**
lnREN	-0.019	**0.005**	-0.008	**0.049**	-0.027	**0.008**
lnURB	0.874	**0.000**	0.389	**0.023**	1.263	**0.000**
Fixed-effect SAC model						
lnGDP	1.059	**0.000**	0.694	**0.002**	1.753	**0.000**
lnGDP2	-0.037	**0.021**	-0.024	**0.035**	-0.061	**0.023**
lnBIO	0.144	**0.000**	0.094	**0.000**	0.237	**0.000**
lnECS	-0.701	**0.000**	-0.464	**0.000**	-1.165	**0.000**
lnTRA	-0.104	**0.001**	-0.070	**0.015**	-0.174	**0.003**
lnREN	-0.015	**0.020**	-0.010	**0.034**	-0.025	**0.022**
lnURB	0.864	**0.000**	0.571	**0.001**	1.435	**0.000**

Source: Research findings

Table 9. The results of direct, indirect and total effects under alternative spatial weights matrices.

Variable	Direct effect		Indirect effect		Total effect	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
Fixed-effect SDM model under four nearest neighbors spatial weights matrix (W_k4)						
lnGDP	1.204	**0.000**	2.745	**0.000**	3.949	**0.000**
lnGDP2	-0.054	**0.001**	-0.164	**0.000**	-0.218	**0.000**
lnBIO	0.268	**0.000**	0.089	0.453	0.357	**0.003**
lnECS	-0.565	**0.000**	-0.442	**0.097**	-1.007	**0.001**
lnTRA	-0.151	**0.000**	-0.048	0.475	-0.199	**0.011**
lnREN	-0.014	**0.039**	0.006	0.693	-0.008	0.615
lnURB	0.709	**0.003**	1.045	0.214	1.753	**0.061**
Fixed-effect SDM model under inverse-distance spatial weights matrix (W_i)						
lnGDP	1.323	**0.000**	3.881	**0.004**	5.204	**0.001**
lnGDP2	-0.062	**0.000**	-0.256	**0.001**	-0.318	**0.000**
lnBIO	0.300	**0.000**	0.744	**0.001**	1.044	**0.000**
lnECS	-0.591	**0.000**	-1.196	**0.007**	-1.787	**0.000**
lnTRA	-0.095	**0.010**	0.283	0.101	0.188	0.296
lnREN	-0.013	**0.048**	0.023	0.294	0.010	0.668
lnURB	0.553	**0.021**	-0.334	0.800	0.219	0.877

Source: Research findings.

Table 10. The results of direct, indirect and total effects of dynamic SDM.

Variable	Short-term effect						Long-term effect					
	Direct effect		Indirect effect		Total effect		Direct effect		Indirect effect		Total effect	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
lnGDP	1.156	**0.000**	2.113	**0.000**	3.269	**0.000**	1.232	**0.000**	2.529	**0.000**	3.761	**0.000**
lnGDP2	-0.046	**0.004**	-0.118	**0.000**	-0.164	**0.000**	-0.051	**0.002**	-0.138	**0.000**	-0.189	**0.000**
lnBIO	0.246	**0.000**	0.323	**0.001**	0.570	**0.000**	0.258	**0.000**	0.397	**0.000**	0.655	**0.000**
lnECS	-0.652	**0.000**	-0.602	**0.013**	-1.254	**0.000**	-0.675	**0.000**	-0.768	**0.005**	-1.442	**0.000**
lnTRA	-0.123	**0.000**	-0.080	0.272	-0.202	**0.009**	-0.126	**0.000**	-0.107	0.189	-0.233	**0.010**
lnREN	-0.011	0.106	0.006	0.619	-0.005	0.772	-0.011	0.122	0.005	0.710	-0.005	0.773
lnURB	0.912	**0.000**	-1.152	**0.065**	-0.240	0.724	0.875	**0.001**	-1.153	0.100	-0.277	0.722

Source: Research findings.

Table 11. The results of direct, indirect and total effects of SDM (Dependent variable: LnCO2).

Variable	Direct effect		Indirect effect		Total effect	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
lnGDP	3.326	**0.000**	0.309	**0.083**	3.635	**0.000**
lnGDP2	-0.166	**0.000**	-0.015	**0.085**	-0.181	**0.000**
lnBIO	0.292	**0.000**	0.027	**0.071**	0.318	**0.000**
lnECS	-0.261	**0.001**	-0.024	0.138	-0.285	**0.001**
lnTRA	0.047	0.129	0.004	0.317	0.051	0.130
lnREN	-0.027	**0.000**	-0.002	0.111	-0.029	**0.000**
lnURB	1.090	**0.000**	0.102	**0.094**	1.192	**0.000**

Source: Research findings.

Conclusions

This study investigated the spatial direct, indirect, and total effects of determinants on the ecological footprint in 17 MENA countries during 2001-2021. This research provides a valuable contribution to the literature by investigating the spatial effects of economic structure and trade openness on the environmental degradation using the SDM model. The main findings are briefly summarized as follows. First, the local country's ecological footprint is significantly affected by the ecological footprint of other countries in the MENA region. Second, the economic structural changes and trade openness have significantly negative effect on the ecological footprint, indicating development of tertiary industry and increase in international trade can improve the ecological sustainability. Third, there is inverted U-shaped EKC hypothesis for the ecological footprint. Fourth, renewable energy consumption reduces the ecological footprint, however, biocapacity and urbanization exacerbates the ecological degradation. The results of robustness analyses confirm that the environmental effects of influencing factors-particularly structural economic changes-are stable across a wide set of spatial model specifications and support the consistency of the findings. According to the findings, some policy implications are provided to reach Sustainable Development Goals (SDGs). First, the significant effect of structural economic transformation shows that accelerating diversification away from resource-intensive and carbon-heavy industries toward high-value, knowledge-based services can substantially mitigate ecological pressures. Countries with large ecological footprints such as Saudi Arabia, the UAE, and Iran should prioritize green services, digital industries, and low-carbon tourism as part of their long-term diversification strategies (SDG 8, SDG 12, SDG 13). Second, although trade liberalization did not produce significant spatial spillovers, aligning trade policies with environmental standards such as promoting imports of clean technologies, incentivizing low-carbon exports, and applying green procurement rules can enhance the ecological benefits of trade openness (SDG 8, SDG 12). Third, the footprint-reducing impact of renewable energy consumption confirms the need for large-scale expansion of solar and wind capacities, reform of fossil-fuel subsidies, and adoption of decentralized clean-energy systems, particularly in high-consumption economies across the region (SDG 7, SDG 13). Fourth, given the adverse influence of urbanization on ecological sustainability, MENA governments must adopt more sustainable urban-development models, including public transport electrification, circular-economy waste strategies, and stricter green-building codes in rapidly expanding cities like Riyadh, Tehran, Dubai, and Cairo (SDG 11, SDG 12, SDG 13). Fifth, stronger regional cooperation through shared renewable-energy markets, harmonized environmental regulations, technology-transfer platforms, and joint carbon-reduction initiatives—can amplify national efforts and reduce ecological footprint across borders. A regional clean-energy alliance involving Saudi Arabia, the UAE, Iran, Morocco, and Egypt would be an especially effective mechanism for accelerating progress toward SDGs 7, 12, and 13. Finally, Although this research provides an important contribution concerning the spatial effects of economic structural changes and trade openness on the ecological sustainability, future research can extend the existing literature by investigating other possible determinants such as artificial intelligence, energy poverty, governance, and globalization and by conducting panel quantile regression and panel threshold models.

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ارزیابی اثرات تغییرات ساختاری اقتصادی و باز بودن تجاری بر پایداری اکولوژیکی: مطالعه موردی منطقه منا (خاورمیانه و شمال آفریقا)

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چکیده

رشد اقتصادی ناشی از فعالیت‌های ناپایدار، فشار فزاینده‌ای بر محیط زیست وارد می‌کند و منجر به تخریب محیط زیست می‌شود. در حالی که تحقیقات در مورد پایداری زیست‌محیطی در منطقه MENA (خاورمیانه و شمال آفریقا) در حال گسترش است، اثرات فضایی تغییرات ساختاری اقتصادی و باز بودن تجارت بر ردپای زیست‌محیطی همچنان ناشناخته مانده است. این مطالعه با بررسی اینکه آیا تحولات ساختاری در اقتصاد و تجارت، اثرات مستقیم و سرریز فضایی قابل توجهی بر ردپای زیست‌محیطی در کشورهای MENA از سال ۲۰۰۱ تا ۲۰۲۱ اعمال می‌کنند، به این شکاف می‌پردازد. برای این منظور، از آزمون موران I استفاده کردیم و مدل SDM با اثر ثابت را به کار بردیم. برای اطمینان از یافته‌ها، استحکام نتایج خود را در مدل‌های فضایی جایگزین و سایر ماتریس‌ها بررسی کردیم. نتایج نشان داد که وابستگی فضایی مثبت قابل توجهی در ردپای زیست‌محیطی وجود دارد که نشان می‌دهد ردپای زیست‌محیطی یک کشور تحت تأثیر همسایگانش است. ما دریافتیم که تغییرات ساختاری اقتصادی نقش مهمی در کاهش ردپای زیست‌محیطی، چه به طور مستقیم و چه از طریق اثرات سرریز، ایفا می‌کنند. به طور مشابه، باز بودن تجارت تأثیر منفی قابل توجهی بر ردپای زیست‌محیطی داشت. با این حال، اثر سرریز قابل توجه نبود. نتایج بررسی‌های پایداری، تأثیر زیست‌محیطی تغییرات ساختاری اقتصادی و باز بودن تجارت را قوی و تحت تأثیر فرضیات خاص مدل قرار نداده است. این یافته‌ها بر نیاز دولت‌های منطقه خاورمیانه و شمال آفریقا به اولویت‌بندی بازسازی اقتصادی و ترویج پذیرش فناوری‌های سازگار با محیط زیست از طریق سیاست‌های تجاری استراتژیک و کاهش موانع تجاری تأکید می‌کند.