



Unraveling the Nexus: An ARDL Analysis of Renewable Energy Consumption, Tourism, and FDI on Tunisia's Ecological Footprint



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Abstract: This study investigates the dynamic impacts of renewable energy consumption, tourism, and foreign direct investment (FDI) on Tunisia's ecological footprint from 1994 to 2022. We apply the Autoregressive Distributed Lag (ARDL) approach to examine these relationships. The results confirm cointegration among the variables and reveal distinct short-run and long-run dynamics. The long-run results indicate that tourism significantly increases ecological footprint, whereas FDI decreases it. Most notably, renewable energy consumption exhibits no statistically significant long-run impact. However, renewable energy significantly moderates environmental degradation in the short term. Additionally, FDI and tourism demonstrate complex, lagged short-run effects. The findings underscore the critical importance of distinguishing between short-run and long-run environmental impacts. The study concludes by offering specific policy recommendations to enable Tunisia to balance economic development with environmental sustainability.

Keywords: Autoregressive Distributed Lag; Ecological footprint; Foreign direct investment; Renewable energy; Tourism

1 Introduction

Environmental sustainability has become a central concern for developing economies seeking to balance economic growth with ecological conservation. For these nations, the challenge lies not in choosing between development and environmental protection, but in understanding how specific economic activities contribute to, or mitigate, ecological degradation. The ecological footprint, which measures human demand on natural resources, provides a comprehensive indicator for assessing this balance [1]. Understanding its determinants is essential for informed policymaking, particularly in countries undergoing rapid economic transformation.

Tunisia presents an important case study among upper-middle-income nations pursuing diversified growth. The country has experienced substantial expansion across three key sectors: renewable energy, tourism, and foreign direct investment (FDI). Each of these sectors carries potential environmental implications that remain inadequately understood, particularly regarding their relative contributions to Tunisia's ecological footprint.

Tunisia's renewable energy sector has expanded under the 2030 National Energy Transition Strategy, which targets a 35% share of renewables in total energy consumption by 2030 [2]. Despite these ambitions, fossil fuels accounted for over 85% of Tunisia's energy consumption in 2021 [3]. This disconnect between policy targets and current energy structure raises a critical question: to what extent does renewable energy consumption actually reduce environmental pressure? The answer is not self-evident, as renewable capacity must reach sufficient scale and displace fossil fuel use sufficiently to generate measurable ecological benefits.

Tourism represents a second major pillar of Tunisia's economy, contributing 14% to GDP and attracting over nine million visitors annually [4]. While tourism generates employment and foreign exchange, it also intensifies pressure on water resources, increases waste generation, and produces carbon emissions from transportation and infrastructure development [5]. Whether tourism's economic benefits outweigh its environmental costs remains an open question, particularly in a country where coastal ecosystems face mounting stress from concentrated tourist activity.

FDI constitutes the third key sector, with Tunisia receiving \$660 million in FDI inflows during 2022, concentrated in energy, manufacturing, and tourism [6]. FDI can promote economic growth and technology transfer, but it may also accelerate resource depletion and pollution, particularly when directed toward ecologically intensive industries [7]. The net environmental effect of FDI depends on whether investments bring cleaner technologies (the “pollution halo” effect) or simply relocate polluting activities to less regulated jurisdictions (the “pollution haven” effect).

Despite the importance of these three sectors, existing research provides an incomplete picture of their joint environmental impact. Previous studies have typically examined each variable in isolation or focused narrowly on carbon emissions rather than the broader ecological footprint. More critically, the literature rarely distinguishes between short-run and long-run effects—a distinction essential for effective policy design. Policies that yield immediate environmental improvements may prove ineffective over longer horizons, while those with delayed benefits may be prematurely abandoned if evaluated only on short-term results.

This study addresses these gaps by examining the dynamic impacts of renewable energy consumption, tourism, and FDI on Tunisia’s ecological footprint from 1994 to 2022. We make three primary contributions. First, we employ the ecological footprint as a comprehensive environmental indicator, capturing multiple dimensions of resource demand beyond carbon emissions alone. Second, we apply the Autoregressive Distributed Lag (ARDL) bounds testing approach to distinguish empirically between short-run dynamics and long-run equilibrium relationships. This temporal distinction is critical for informing policy sequencing and evaluating the time horizons over which different interventions operate. Third, we provide country-specific evidence for Tunisia, offering insights relevant to other developing economies with similar structural characteristics.

The remainder of this paper is organized as follows. Section 2 presents the theoretical framework underpinning the analysis. Section 3 reviews the empirical literature on the relationships between renewable energy, tourism, FDI, and ecological footprint. Section 4 describes the data sources, variable definitions, and econometric methodology. Section 5 reports and discusses the empirical results, including diagnostic tests and robustness checks. Section 6 concludes with policy implications and directions for future research.

2 Theoretical Framework

This study is grounded in a set of interconnecting theoretical traditions explaining the complex interdependencies between economic action, energy consumption, investment, and environmental degradation. One needs to be familiar with these theories to interpret the empirical evidence and position the contribution of renewable energy, tourism, and FDI to Tunisia’s ecological footprint.

2.1 The Environmental Kuznets Curve Hypothesis

One of the pillars of environmental economics, the Environmental Kuznets Curve (EKC) hypothesis demonstrates an inverted U-shaped relationship between per capita income and environmental degradation [8]. Early in economic development, industrialization and expansion lead to higher use of resources and pollution, elevating environmental degradation. With a point of income achieved, the correlation is flipped. It is owing to a combination of factors: structural shifting towards service economies away from the manufacturing economy, embracing more efficient and cleaner technology, and greater demand from consumers for a clean environment, which leads to stricter environmental regulations.

For Tunisia, which is an upper-middle-income country, it is critical to test the implicit background of the EKC. Our independent variables (tourism, FDI) may have a mediated relation with the ecological footprint via the level of development in the country. If Tunisia is at the rising stage of the EKC, tourism-induced growth would significantly boost its ecological footprint. Conversely, if it is approaching or has approached the turning point, we can see that economic activities like FDI begin to implement greener technologies, thereby relieving the pressure on the environment.

2.2 The Pollution Haven Hypothesis vs. The Pollution Halo Hypothesis

The environmental effect of FDI is theoretically indefinite and is explained by two competing hypotheses.

The Pollution Haven Hypothesis suggests that the least regulated countries are “pollution havens” for environmentally polluting industries fleeing more highly regulated developed nations [9]. From this viewpoint, FDI, particularly in manufacturing and extractive industries, would lead to an expanded ecological footprint by the host country as firms seek to lower costs associated with compliance with environmental standards.

On the other hand, the Pollution Halo Hypothesis anticipates that multinational corporations are inclined to bring in better, environmentally friendly technologies and management practices to the host nations. Technology and knowledge spilling over to indigenous companies would lead to a broad improvement in the environmental performance, a “halo” effect. The theory predicts FDI to reduce the ecological footprint by employing better resource efficiency and cleaner production mechanisms.

The sign and interpretation of the FDI coefficient in our model will provide empirical evidence as to which of these two theories is more relevant in the Tunisian context.

2.3 Theories of Sustainable Development and the Role of Renewable Energy

Sustainable Development, once arguably best defined by Brundtland [10] as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, provides the normative foundation for this publication. It requires that economic development be delinked from environmental degradation.

In this context, the renewable energy transition is a cornerstone pillar. The theory believes that replacing fossil fuels with sustainable energy sources (solar, wind, hydro) ought, in theory, to reduce the environmental footprint right away through restricting carbon emissions and the land and resource cost of extracting and burning fossil fuels [11]. However, its success hinges on, *inter alia*, the size of deployment, the energy mix, and rebound effects whereby more efficiency is matched by higher consumption. Our estimates verify whether the hypothesized gain in this theoretical advantage indeed materializes in the short and long run for Tunisia.

3 Empirical Literature Review

The rapid pace of economic growth, globalization, and increasing environmental awareness has made understanding the complex relationship between human activity and ecological sustainability increasingly important. The ecological footprint has emerged as a widely used indicator to account for human demand on natural resources and the health of ecosystems. It captures the extent to which human consumption exceeds the regenerative capacities of ecosystems, providing critical information on the long-run viability of current development paths. Underpinning processes of resource abuse and ecological deterioration is a network of driving forces that must be understood by any country attempting to balance environmental stewardship with economic progress.

The impact of renewable energy, tourism, and FDI on the ecological footprint is multidimensional and sometimes contradictory. This review synthesizes existing empirical studies to establish the foundation for the present analysis.

3.1 The Nexus Between Renewable Energy and Ecological Footprint

A substantial body of research points to the beneficial role of renewable energy in mitigating environmental degradation. The consumption of renewable energy generally reduces the ecological footprint because it mitigates CO₂ emissions and reduces dependence on fossil fuels [11].

Supporting this, Sharif et al. [12] utilized the Quantile ARDL approach to analyze the impact of energy consumption on Turkey’s ecological footprint from 1965 to 2017. Their results indicated that the impact of renewable energy consumption on diminishing the ecological footprint is highly significant at all quantiles, showing a long-run positive effect. Conversely, economic growth and the use of non-renewable energy were found to positively affect the ecological footprint.

Further reinforcing this view, Danish and Khan [13] analyzed the drivers of the ecological footprint with a special interest in renewable energy. Using a panel dataset of 116 countries, their results revealed a strong negative relation between the ecological footprint and renewable energy, indicating that an increase in renewable energy use decreases ecological footprints and contributes positively to environmental sustainability.

A broader study by Özcan [14], using quantile regression analysis for 131 countries, also suggested that increased power generation from renewables has a countering effect on ecological footprints, positing that cleaner energy source adoption can mitigate environmental degradation.

3.2 Tourism Activities and Their Environmental Implications

Empirical evidence on tourism’s environmental impact remains mixed. While sustainable tourism practices may have the potential to reduce pressure, mass tourism tends to cause environmental degradation through intensive resource use and infrastructure development [15].

Koyuncu [16] found significant positive effects on the ecological footprint in Mediterranean countries. Conversely, Ozturk et al. [17] reported that higher tourism income could improve environmental performance in upper-middle-income nations. Yaqoob et al. [18] further confirmed this context-specificity, observing positive effects in China and Pakistan but negative effects in India.

3.3 The Dual Role of Foreign Direct Investment

The relationship of FDI to ecological footprint is complex and is characterized by two competing hypotheses: the pollution haven hypothesis and the pollution halo hypothesis. Some studies suggest that FDI increases the ecological footprint, supporting the pollution haven hypothesis, while others find that, often in conjunction with green innovation, FDI could reduce it, helping the pollution halo hypothesis [19].

Evidence from Tunisia by Hfaiedh and Bardi [20] supports the negative view. Applying the ARDL method, they observed that FDI harms environmental quality, a result they attribute to FDI being concentrated in sectors such as textiles, which are not capital-intensive. They also found that corruption exacerbates this negative impact.

In contrast, a study on Finland by Georgescu and Kinnunen [21] presented a different picture. Using the ARDL model, they found that FDI hurts the ecological footprint, implying that foreign investments could promote more sustainable practices and cleaner technologies in the Finnish context.

Further complicating the narrative, a recent study on Costa Rica by Hechmi and Chaabouni [22] reveals that the environmental impact of FDI is also temporally dynamic. Their analysis demonstrates a clear dichotomy: FDI mitigates carbon emissions in the short run, likely through initial green investments, but exacerbates them in the long run due to the cumulative effects of industrialization and heightened energy consumption.

The cross-country analysis by Yaqoob et al. [18] further illustrates this duality. Their results showed that FDI depicts increasing environmental degradation in some cases but improves the ecosystem in others, such as in the UK. Similarly, Özcan [14] found that, on aggregate across 131 countries, registered FDI inflows intensified environmental impacts by increasing ecological footprints.

This literature review indicates that the relationship between key economic factors and the ecological footprint is complicated and often contradictory. Findings on the roles of renewable energy consumption, tourism, and FDI are mixed, varying with specific national contexts, levels of economic development, and methodological approaches.

Such inconsistent findings call for further targeted research. While individual relationships have been explored, there is a need for studies that integrate these variables within a specific national context to provide a comprehensive picture. This study, therefore, tries to fill this gap by focusing specifically on Tunisia, combining these economic factors into a single analytical framework, using the most recent data, and resorting to the ARDL econometric technique to distinguish between short-run and long-run effects. This analysis is expected to yield more nuanced insights into how these factors jointly relate to environmental sustainability in Tunisia, providing valuable information for policymakers in Tunisia and other developing economies with similar profiles.

4 Materials and Methods

4.1 Data Sources and Variables Description

This study examines the relationship between ecological footprint, renewable energy consumption, tourism, and FDI in Tunisia. The temporal scope of our data is from 1994 to 2022, thus enabling a full and extensive review.

Table 1 presents the variables, measurement units, and data sources.

Table 1. Variables description

Variable	Symbol	Measurement Units	Data Sources
Ecological footprint	$LnEF$	Global hectares per capita	Global Footprint Network
Renewable energy consumption	$LnRENE$	% of total final energy consumption	World Development Indicators
Tourism	$LnTOUR$	Total number of arrivals in the host country	World Development Indicators
Foreign direct investment	$LnFDI$	Net inflows (% of GDP)	World Development Indicators

$LnEF$, the dependent variable, represents the ecological footprint at global hectares per capita. Key independent variables include $LnRENE$, reflecting renewable energy consumption as the share of total final energy consumption; $LnTOUR$ measures tourism as the total number of arrivals in the host country, and $LnFDI$ reflects foreign direct investment, net inflows as a share of GDP. All variables are transformed into natural logarithms (denoted by the prefix Ln) to interpret the coefficients as elasticities and to reduce heteroscedasticity. This approach is commonly used in econometric studies because it helps make the data more comparable and allows the results to be interpreted in terms of percentage changes, which is easier to understand when analyzing economic relationships.

The model follows a parsimonious specification. It includes only the core variables of interest: renewable energy, tourism, and FDI. This approach suits the ARDL framework and accommodates the available sample size. Other controlling factors, such as GDP per capita or trade openness, could have been considered plausible determinants of the ecological footprint, but we have excluded them to avoid multicollinearity issues and to keep the stationarity properties of the model manageable. This approach helps in a clearer interpretation of the direct relationships under investigation.

4.2 Autoregressive Distributed Lag and Error Correction Model Estimation Models

Understanding long-run relationships within an econometric framework is essential for assessing the persistent effects of economic variables and informing long-run policy decisions [23]. We examine the impact of renewable energy consumption, tourism, and FDI on Tunisia's ecological footprint using the Autoregressive Distributed Lag and Error Correction Model (ARDL-ECM) framework. We selected the ARDL-ECM approach for its flexibility

and reliability in handling diverse data relationships. We consider this method particularly suitable for datasets with mixed stationarity properties, variables integrated at level or first difference, as it overcomes problems associated with unit root pretesting [24].

We employed the ARDL approach with the bounds testing cointegration method, introduced by Pesaran et al. [25], to analyze both short-run and long-run associations and dynamic interactions among the variables [26]. This approach offers flexibility in selecting lag orders and provides a better fit to the data. It also yields, through the ECM, the speed at which the system returns to long-run equilibrium following short-run shocks. We specify the model in Eq. (1):

$$LnEF_t = \alpha_0 + \alpha_1 LnRENE_t + \alpha_2 LnTOUR_t + \alpha_3 LnFDI_t + \varepsilon_t \quad (1)$$

where, Ln in each variable denotes the natural logarithm transformation, EF refers to ecological footprint, $RENE$ indicates renewable energy consumption, $TOUR$ indicates tourism, FDI refers to foreign direct investment, and ε_t indicates the error term.

Eq. (2) outlines the ARDL regression model utilized in this study.

$$\begin{aligned} \Delta LnEF_t = & \alpha_0 + \sum_{k=1}^n \alpha_1 \Delta LnEF_{t-k} + \sum_{k=1}^n \alpha_2 \Delta LnRENE_{t-k} + \sum_{k=1}^n \alpha_3 \Delta LnTOUR_{t-k} + \sum_{k=1}^n \alpha_4 \Delta LnFDI_{t-k} \\ & + \lambda_1 LnEF_{t-1} + \lambda_2 LnRENE_{t-1} + \lambda_3 LnTOUR_{t-1} + \lambda_4 LnFDI_{t-1} + \varepsilon_t \end{aligned} \quad (2)$$

where, Δ represents the first difference, α_1 through α_4 are the short-run coefficients, and λ_1 through λ_4 are the long-run coefficients.

5 Results and Discussion

5.1 Descriptive Statistics

Table 2 presents the descriptive statistics of the variables.

Table 2. Descriptive statistics

Variable	Obs.	Mean	Max	Min	Std. Dev.	VIF
<i>LnEF</i>	29	0.199	0.292	-0.032	0.086	-
<i>LnRENE</i>	29	1.130	1.207	1.064	0.037	1.21
<i>LnTOUR</i>	29	6.730	6.974	6.304	0.160	1.26
<i>LnFDI</i>	29	0.35	0.974	-0.046	0.216	1.50

Note: *EF*, ecological footprint; *RENE*, renewable energy consumption; *TOUR*, tourism; *FDI*, foreign direct investment.

The mean value of ecological footprint, *LnEF*, equals 0.2, with a maximum value of 0.292 and a minimum of -0.032, which shows relatively low variability, Std. Dev. = 0.086. Renewable energy consumption (*LnRENE*) has a mean of 1.13, the standard deviation being 0.037, suggesting minimal fluctuations. The mean of the *LnTOUR* equals 6.73; this variable is more dispersed, as shown by Std. Dev. = 0.16. Finally, *LnFDI* shows the highest variability (Std. Dev. = 0.216), with values ranging from -0.046 to 0.974. The variance inflation factor (VIF) test is used to eliminate any uncertainty regarding collinearity, as reported in Table 2. Since all VIF values are below 5, there is no severe multicollinearity in this model, and no corrective measures (such as variable elimination or transformation) are needed.

5.2 Unit Root Test

Unit root tests form an essential component of time series analysis. They serve several important functions. They indicate stationarity or non-stationarity of a time series and therefore provide grounds for choosing the proper technique of modelling and for avoiding spurious regressions. In fact, with unit root tests, one can learn about the long-run behavior of economic variables, improve forecasting, and lay a platform for cointegration analysis. The results from the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test for unit roots are presented in Table 3.

As shown in Table 3, the unit root tests reveal a mixed order of integration among the variables. *LnEF* exhibits stationarity at both level and first difference, indicating that it can be treated as I(1) for ARDL analysis, a common approach when variables show evidence of integration at both orders, particularly in small samples. *LnRENE* and *LnFDI* are stationary at level at the 5% level but become strongly stationary after differencing, while *LnTOUR* is

clearly I(1). This mixture of I(0) and I(1) variables, with no evidence of I(2), validates the application of the ARDL bounds testing approach, which is specifically designed for such integration properties.

Table 3. The unit root test results

Variable	ADF Test		PP Test		Remarks
	Level Prob.	1 st Diff. Prob.	Level Prob.	1 st Diff. Prob.	
<i>LnEF</i>	0.0024***	0.0000***	0.0026***	0.0000***	I(0), I(1)
<i>LnRENE</i>	0.0192**	0.0000***	0.0211**	0.0000***	I(0), I(1)
<i>LnTOUR</i>	0.6574	0.0000***	0.7382	0.0000***	I(1)
<i>LnFDI</i>	0.0151**	0.0000***	0.0121**	0.0000***	I(0), I(1)

Note: ADF, Augmented Dickey-Fuller; PP, Phillips-Perron; *EF*, ecological footprint; *RENE*, renewable energy consumption; *TOUR*, tourism; *FDI*, foreign direct investment. *** and ** indicate 1% and 5% significance levels, respectively.

5.3 Determining the Optimal Lag Structure in the Autoregressive Distributed Lag Model

Table 4 presents the lag order selection criteria based on the unrestricted VAR. The optimal lag structure of the ARDL model is selected with the Akaike Information Criterion (AIC). According to this, both the dependent variable (*LnEF*) and the fixed regressors included in the model have a maximum of four lags.

Table 4. Optimal lag selection

Lag	LL	LR	df	Prob.	FPE	AIC	HQIC	SBIC
0	105.763	-	-	-	3.4e-09	-8.141	-8.08691	-7.94598*
1	125.111	38.698	16	0.001	2.7e-09*	-8.4089	-8.13845*	1.87
2	137.196	24.169	16	0.086	4.1e-09	-8.09567	-7.60886	1.94
3	157.942	41.493	16	0.000	3.8e-09	-8.47539	-7.77222	1.38
4	179.062	42.239*	16	0.000	5.4e-09	-8.88494*	-7.9654	1.52

Note: LL, log likelihood; LR, likelihood ratio; df, degrees of freedom; FPE, final prediction error; AIC, Akaike information criterion; HQIC, Hannan–Quinn information criterion; SBIC, Schwarz–Bayesian information criterion. * indicates lag order selected by the criteria.

5.4 Autoregressive Distributed Lag Bound Test

We performed a bounds test to assess the long-run relationship among the variables, as shown in Table 5. This test detects cointegration regardless of the variables' order of integration.

Table 5. Bound test for cointegration analysis

Test Statistic	Value	Significance Level	I(0)	I(1)
F-statistic	7.619	10%	2.72	3.77
K	3	5%	3.23	4.35
		1%	4.29	5.61

The computed F-statistic of 7.62 exceeds the critical upper bound values at the 1%, 5%, and 10% significance levels. These robust results provide strong evidence to reject the null hypothesis of no cointegration. We therefore conclude that a significant long-run equilibrium relationship exists among the variables.

5.5 Long-Run Analysis

Table 6 reports the estimated long-run coefficients from the ARDL model.

Table 6. Estimated long-run coefficients

Dependent Variable: <i>LnEF</i>				
Variable	Coeff.	Std. Err.	t-Stat.	Prob.
<i>LnRENE</i>	0.035	0.230	0.150	0.882
<i>LnTOUR</i>	0.611***	0.081	7.580	0.000
<i>LnFDI</i>	-0.117**	0.056	-2.090	0.012
C	-7.712***	2.071	-3.720	0.002

Note: *EF*, ecological footprint; *RENE*, renewable energy consumption; *TOUR*, tourism; *FDI*, foreign direct investment; C, constant. *** and ** indicate 1% and 5% significance levels, respectively.

From the ARDL model, the estimated long-run coefficients revealed that *LnTOUR* and *LnFDI* had significant effects on *LnEF*, while *LnRENE* did not. Specifically, a 1% increase in tourism (*LnTOUR*) increased *LnEF* by 0.61%, whereas a 1% increase in foreign direct investment (*LnFDI*) reduced *LnEF* by 0.12%. These findings suggest (present-interpretation) that tourism-enhancing policies may increase environmental degradation, while FDI appears to have a mitigating effect. However, renewable energy consumption showed no significant long-run impact on ecological footprint.

5.6 Short-Run Dynamics

Table 7 reports the ECM results.

Table 7. Error Correction Model (ECM) regression

Dependent Variable: <i>LnEF</i>				
Variable	Coeff.	Std. Err.	t-Stat.	Prob.
D(<i>LnEF</i> (-1))	1.953***	0.441	4.427	0.002
D(<i>LnEF</i> (-2))	0.772**	0.245	3.153	0.014
D(<i>LnEF</i> (-3))	0.153	0.116	1.322	0.223
D(<i>LnRENE</i>)	-0.652*	0.325	-2.008	0.080
D(<i>LnTOUR</i>)	0.480***	0.076	6.278	0.000
D(<i>LnTOUR</i> (-1))	-1.478***	0.256	-5.778	0.000
D(<i>LnTOUR</i> (-2))	-1.157***	0.199	-5.815	0.000
D(<i>LnTOUR</i> (-3))	-0.590**	0.220	-2.686	0.028
D(<i>LnFDI</i>)	-0.053	0.038	-1.380	0.205
D(<i>LnFDI</i> (-1))	0.284***	0.057	4.999	0.001
D(<i>LnFDI</i> (-2))	0.248***	0.052	4.729	0.002
D(<i>LnFDI</i> (-3))	0.201***	0.048	4.218	0.003
CointEq(-1)	-3.909***	0.577	-6.777	0.000
R ²	0.9107			
Adjusted R ²	0.8214			

Note: *EF*, ecological footprint; *RENE*, renewable energy consumption; *TOUR*, tourism; *FDI*, foreign direct investment. ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively.

As shown in Table 7, the highly significant positive coefficients of D(*LnEF*(-1)) and D(*LnEF*(-2)) indicated that past values of ecological footprint strongly influenced its current value, confirming a path-dependent process. Both D(*LnEF*(-1)) and D(*LnEF*(-2)) exhibited strong effects, while the effect of D(*LnEF*(-3)) was insignificant. This suggests (present - interpretation) a decaying pattern in short-run dynamics. This suggests a decaying pattern of the short-run effect. On the other hand, 1% increase in renewable energy (*LnRENE*) exerts a short-run decrease in ecological footprint by 0.65%. The current year's improvement in tourism (D(*LnTOUR*)) positively influences Tunisian's ecological footprint in the short term, while improvements from the previous years (D(*LnTOUR*(-1)), D(*LnTOUR*(-2)), and D(*LnTOUR*(-3))) have a negative impact. Opposite results are observed for FDI, the current year's improvement in FDI (D(*LnFDI*)) negatively influences Tunisian's ecological footprint in the short term, while improvements from the previous years (D(*LnFDI*(-1)), D(*LnFDI*(-2)) and D(*LnFDI*(-3))) have a positive impact. The highly significant error correction term (ECT) (CointEq = -3.909, $p < 0.01$) confirms a stable long-run relationship among the variables. The magnitude of the coefficient, exceeding -1, reflects the dynamic specification of the model with multiple lags; in this context, the ECT captures the cumulative adjustment process across periods rather than a simple annual correction proportion. The large coefficient and *t*-statistic (-6.777) provide strong evidence of cointegration and indicate that deviations from long-run equilibrium trigger substantial corrective forces. This finding underscores the importance of distinguishing between short-run dynamics and long-run equilibrium relationships when designing environmental policy.

5.7 Diagnostic Tests

The estimators from ARDL are reliable only if there is no heteroscedasticity and serial correlation. Several diagnostic tests are, therefore, performed to check the presence of some of the usual problems like autocorrelation, heteroskedasticity, residual normality, and model stability.

We applied several diagnostic tests, including the Breusch-Godfrey serial correlation Lagrange multiplier (LM) test, Cameron and Trivedi's information matrix (IM) test decomposition, the Jarque-Bera normality test, the Ramsey regression equation specification error test (RESET), and the recursive cumulative sum (CUSUM) test. Table 8 reports the results. These results revealed that the model was free from heteroscedasticity and serial correlation, as

indicated by F-statistic and Chi-square p-values exceeding 0.05. The Jarque-Bera statistic of 1.99 ($p = 0.37$) confirmed that the residuals followed a normal distribution. The correct model specification is evident from the outcomes of the RESET test. The entire set of diagnostic tests affirms the statistical significance and reliability of the ARDL model.

Table 8. Diagnostic tests

Diagnostic Test	Coeff.	Prob.	Outcomes
Durbin Watson	1.689	-	No serial correlation exists
Breusch-Godfrey Serial Correlation LM Test	1.046	0.306	No serial correlation exists
Cameron & Trivedi's Decomposition of IM Test	25.00	0.406	No heteroscedasticity exists
Jarque-Bera	1.987	0.370	Residuals are normally distributed
Ramsey RESET Test	1.080	0.377	The model is correctly specified

Note: LM, Lagrange multiplier; IM, information matrix; RESET, regression equation specification error test.

While the CUSUM test (Figure 1a) indicates stability of the recursive residuals, the CUSUM of squares test (Figure 1b) shows a period of instability around the mid-sample period. This suggests a potential change in the variance of the regression coefficients, possibly due to an unmodeled structural break or an external shock affecting the relationship between the variables during that time. Future research could incorporate breakpoint tests to explore this further.

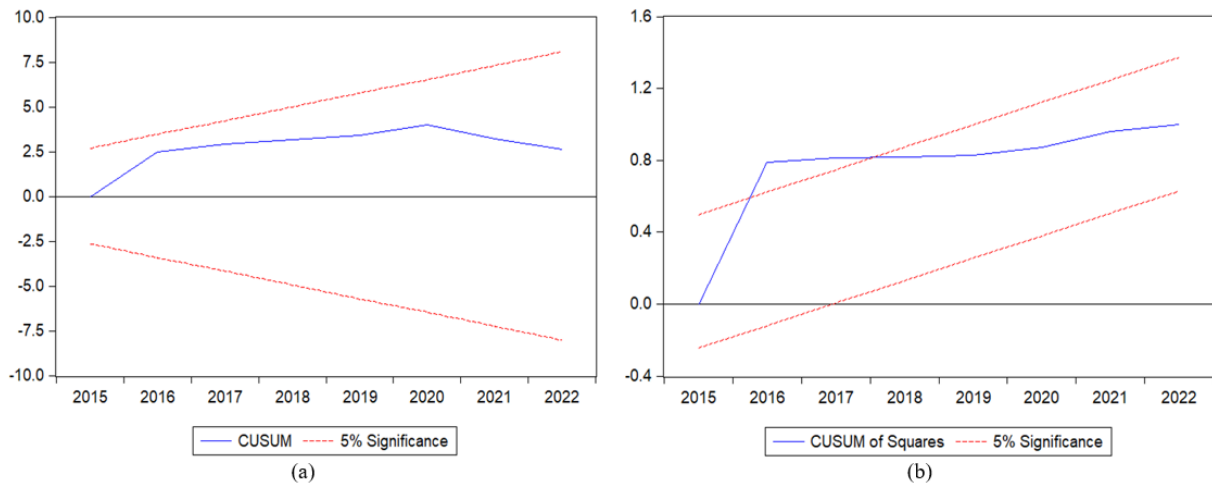


Figure 1. Results of (a) recursive cumulative sum (CUSUM) test and (b) CUSUM squared test

5.8 Robustness Checks

To further validate the long-run relationships, we employ the Dynamic Ordinary Least Squares (DOLS) estimator. The results, presented in Table 9, corroborate the core findings from the ARDL model regarding the drivers of Tunisia's ecological footprint.

Table 9. Dynamic Ordinary Least Squares (DOLS) regression estimates

Long-Run Coefficients (Dependent Variable: $LnEF$)			
Variable	Coeff.	t-Stat.	Prob.
$LnRENE$	0.687*	1.935	0.064
$LnTOUR$	0.293***	4.021	0.001
$LnFDI$	-0.016	-9.262	0.796
C	-1.003*	-1.983	0.058
R^2	0.3578		
Adjusted R^2	0.2808		

Note: EF , ecological footprint; $RENE$, renewable energy consumption; $TOUR$, tourism; FDI , foreign direct investment; C, constant. *** and * indicate 1% and 10% significance levels, respectively.

The positive long-run impact of tourism on the ecological footprint is strong, with a coefficient of 0.293 and a significance level of less than 0.01, and thus supports the finding from ARDL. Nevertheless, unlike in the ARDL

results, renewable energy has a marginally significant positive impact, while the effect of FDI becomes insignificant. This suggests that there is some sensitivity in the magnitude and levels of some coefficients, although the adverse environmental impact of tourism is robust across both estimation approaches.

6 Discussion

The empirical findings of this study reveal a complex and temporally dynamic interplay between economic activities and environmental degradation in Tunisia. The core of our analysis rests on the long-run equilibrium relationship identified among the variables, with the short-run dynamics providing crucial, nuanced insights for policy timing and design. This discussion first examines the long-run effects of tourism, FDI, and renewable energy, then turns to the short-run dynamics, and finally synthesizes the implications of these temporal distinctions.

The long-run coefficients (Table 6) establish the persistent effects of tourism and FDI on Tunisia's ecological footprint. The results indicate that tourism (*LnTOUR*) exerts a significant positive long-run effect, increasing environmental degradation. This finding aligns with studies by Yaqoob et al. [18] in China and Pakistan and Koyuncu [16] in Mediterranean countries.

Several factors explain tourism's detrimental long-run impact in Tunisia. First, tourism remains a carbon-intensive and resource-intensive sector. Popular destinations exhibit per-tourist emissions and water usage well above national averages. Second, tourism infrastructure expansion drives coastal urbanization and land-use change, converting natural habitats into built environments. Third, local waste management systems face chronic strain from the volume of solid waste generated during peak seasons. The aggregate impact of millions of visitors, despite potentially low individual footprints, creates a substantial and lasting ecological burden that conflicts with Tunisia's climate objectives.

In contrast to tourism's detrimental effect, FDI demonstrates a significant negative long-run impact on the ecological footprint, indicating environmental improvement. This result is consistent with Yaqoob et al. [18] in the UK and suggests the dominance of a "pollution halo" effect in the Tunisian context over the long term.

This finding implies that foreign investments may introduce advanced, cleaner technologies and more efficient management practices. After an initial adjustment period, these contributions appear to reduce environmental degradation. The result challenges the pollution haven hypothesis for Tunisia in the long run, suggesting that sustained FDI may flow toward, or stimulate, sectors and practices that are relatively less ecologically intensive. Over time, technological spillovers from foreign firms may also improve environmental performance among domestic enterprises.

While tourism and FDI show clear long-run effects, renewable energy presents a more complex picture. The most notable long-run finding is the statistical insignificance of renewable energy consumption (*LnRENE*). This result requires examination beyond the simplistic explanation of its currently small share in the energy mix.

Several structural factors likely contribute to this insignificance. First, while renewables constitute less than 4% of Tunisia's power mix [27] and the nation remains approximately 97% dependent on natural gas and other fossil fuels [28], the scale problem alone does not fully explain the absence of a long-run effect. Second, the "rebound effect" may be operating: gains from modest renewable capacity may be offset by increased overall energy consumption driven by economic growth, potentially from the same sectors examined in this study (tourism and FDI-led industries). Third, the ecological footprint is a lifecycle metric. It embeds the initial environmental costs of manufacturing, transporting, and installing renewable infrastructure (e.g., solar panels, wind turbines), as well as future decommissioning and disposal costs. If the renewable energy sector itself relies on fossil fuels for its supply chain, its net long-run ecological benefit may be diluted.

These findings underscore that the transition to renewables is not merely an additive process but a systemic one. Achieving a significant long-run reduction in the ecological footprint requires fundamental restructuring of the entire energy grid, industrial processes, and consumption patterns, not simply increasing renewable capacity.

The short-run dynamics (Table 7) reveal a more immediate and, at times, contradictory picture, highlighting the importance of temporal scale in analysis. While long-run effects determine equilibrium outcomes, short-run responses matter for policy timing and the design of immediate interventions.

Renewable energy consumption shows a significant negative short-run effect, reducing the ecological footprint in the immediate term. This finding aligns with Sharif et al. [12] and Danish and Khan [13] and can be attributed to the direct displacement of fossil fuels in electricity generation. When renewable sources enter the grid, they produce an instant reduction in carbon emissions and resource extraction pressures. This demonstrates renewable energy's vital role as a rapid response tool for environmental improvement, even as its long-run effects remain constrained by structural factors.

The short-run effects of tourism are complex and time-dependent. Current-year tourism growth degrades the environment, likely reflecting the immediate strain of peak tourist arrivals on local resources and waste systems. However, the negative coefficients of lagged tourism terms suggest a mitigating effect from previous years' improvements.

This pattern may reflect two possibilities. First, investments in efficiency or environmental management made in response to past tourism growth may take time to become operational. Second, a cyclical pattern may exist whereby

the environmental impact of a tourism boom is partially absorbed or remediated in subsequent years through natural regeneration or policy responses. The lagged negative coefficients suggest that while tourism's immediate effect is harmful, the sector can adapt over short time horizons.

Similarly, FDI exhibits a time-lagged short-run dynamic that contrasts with its long-run benefit. Current-year FDI reduces the ecological footprint, possibly due to the immediate adoption of cleaner standards by newly established foreign firms. However, lagged FDI values show positive impacts, indicating that the scaling up of operations from past investments initially increases environmental degradation.

This dual impact carries important implications. The environmental benefits of FDI are not instantaneous; they materialize only after foreign firms become fully integrated into the local economy, and their technological advantages permeate domestic supply chains. Policymakers should therefore avoid judging FDI's environmental impact based solely on its immediate effects, as the pollution halo emerges only over longer time horizons.

Taken together, these findings reveal a fundamental tension between short-run and long-run environmental outcomes in Tunisia. Renewable energy offers immediate mitigation benefits but lacks a lasting impact under current structural conditions. Tourism consistently degrades the environment across both time horizons, marking it as the primary policy challenge. FDI presents a more hopeful picture, with short-run costs giving way to long-run benefits, but only if investment patterns maintain their current character.

This temporal complexity demands equally nuanced policy responses. Short-run interventions (such as promoting renewable energy adoption) can yield immediate gains, but they must be paired with long-run structural reforms (such as reshaping the tourism model and channeling FDI toward green sectors) to achieve lasting environmental improvement. The path-dependent nature of the ecological footprint, confirmed by the significant lagged effects of all variables, means that today's policy decisions will shape environmental outcomes for years to come.

7 Conclusion and Policy Implications

This study examined the dynamic relationships between renewable energy consumption, tourism, FDI, and Tunisia's ecological footprint from 1994 to 2022 using the ARDL bounds testing approach. The findings reveal three principal insights with implications for environmental policy in developing economies.

First, the environmental effects of economic activities differ fundamentally across time horizons. Tourism consistently increases ecological pressure in both the short and long run, marking it as the primary policy challenge. FDI reduces the ecological footprint in the long term, supporting the pollution halo hypothesis, but exhibits mixed short-run effects. Renewable energy consumption delivers immediate environmental benefits but shows no statistically significant long-run impact under current structural conditions.

Second, the ecological footprint exhibits strong path dependency, with past values significantly influencing current outcomes. The significant ECT confirms that deviations from long-run equilibrium are corrected over time, indicating that environmental trends exhibit persistence. Short-term shocks, whether from tourism surges, FDI inflows, or policy changes, generate effects that linger for years, requiring proactive rather than reactive policy approaches.

Third, temporal complexity demands policy differentiation. Interventions effective in the short run may not yield lasting improvements, while policies with delayed benefits risk premature abandonment if evaluated solely on immediate results.

These findings carry specific implications for Tunisia's environmental strategy. In the tourism sector, the persistent positive effect on ecological footprint justifies a structural shift from volume-based mass tourism to a high-value, low-impact model. Policy mechanisms should incentivize environmental certification and resource efficiency while internalizing environmental costs through targeted measures.

For FDI, the long-run pollution halo effect suggests that Tunisia should actively attract investments in cleaner technologies and sustainable sectors. Screening mechanisms that prioritize renewable energy, energy efficiency, and circular economy projects can amplify these environmental benefits while mitigating short-run adjustment costs.

In renewable energy policy, the contrast between significant short-run mitigation and insignificant long-run effects indicates that capacity expansion alone is insufficient. Complementary investments in grid modernization, storage infrastructure, and measures to counter rebound effects are necessary to translate immediate gains into lasting ecological improvement.

More broadly, the path-dependent nature of environmental outcomes supports the application of strategic environmental assessments to all major economic policies and development plans. Such assessments would identify potential ecological consequences before development pathways become locked in, enabling preventative rather than corrective intervention.

Several limitations suggest directions for future research. First, while this study focused on three key sectors, incorporating additional variables such as technological innovation, institutional quality, and trade openness could provide a more complete picture. Second, extending the analysis to sectoral disaggregation, examining FDI by industry type or tourism by segment, would reveal whether environmental effects vary within these broad categories.

Third, comparative studies across multiple North African countries could establish whether Tunisia's patterns reflect national specificities or regional dynamics.

In sum, this study demonstrates that harmonizing economic development with environmental sustainability in Tunisia requires not sectoral promotion or restraint per se, but strategic differentiation between short-run and long-run policy instruments. The challenge lies not in choosing between growth and environmental protection, but in aligning policy time horizons with the temporal reality of ecological outcomes.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

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