

Article

Environmental Degradation, Renewable Energy, Technological Innovation, and Foreign Direct Investment as Determinants of Tourism Development in Tunisia: An Autoregressive Distributed Lag–Fully Modified Ordinary Least Squares Analysis

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Abstract

This study examines how tourism development in Tunisia responds to environmental degradation, renewable energy consumption, technological innovation, and foreign direct investment. Using annual data for 1990–2023, we apply the Autoregressive Distributed Lag (ARDL) bounds approach to identify long-run equilibria and short-run dynamics and validate the results with Fully Modified Ordinary Least Squares (FMOLS). The bounds tests confirm stable long-run relationships among tourism development and its structural determinants—environmental degradation, renewable energy, technological innovation, and foreign direct investment. The empirical results show that environmental degradation depresses tourism development in the long run, whereas renewable energy and technological innovation promote it. Foreign direct investment provides the strongest positive contribution. Complimentary Granger causality tests confirm unidirectional causality from environmental degradation, renewable energy, and technological innovation to tourism development, and bidirectional causality between tourism and foreign direct investment, validating the robustness and direction of influences among variables. Short-run effects appear weaker and occasionally mixed; however, the negative and highly significant error-correction term indicates convergence toward equilibrium. The FMOLS estimates closely match the ARDL results, providing further confidence in the results. Accordingly, policy-makers should bolster environmental management, increase renewable energy as part of tourism infrastructure, advance digital and eco-innovation, and attract FDI in cleaner technologies and higher standards of services. This study fills conceptual and regional evidence gaps by integrating environmental, technological, and financial dimensions within a unified framework. It offers practical guidance consistent with the Sustainable Development Goals; specifically, Goals 7 (clean energy), 8 (sustainable growth and jobs), and 13 (climate action).

Keywords: tourism development; environmental degradation; renewable energy; technological innovation; FDI; sustainability transition; ARDL-FMOLS cointegration methods; Tunisia



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1. Introduction

Tourism occupies a strategic position in Tunisia's economy and remains a key driver of foreign currency, value-added, and employment. Within the North African context, Tunisia attracts fewer visitors than Morocco and Egypt but maintains a higher tourism intensity relative to its population and a stronger regulatory focus on sustainability. According

to the [United Nations World Tourism Organization \(2024\)](#), Tunisia ranked third in the region for international arrivals—behind Egypt and Morocco but ahead of Algeria and Libya—accounting for approximately 12 percent of North Africa’s total inbound visitors. Before the coronavirus pandemic, the tourism industry’s direct GDP contribution was approximately 8%, underscoring its macroeconomic significance and export potential ([Organization for Economic Co-Operation and Development, 2023](#)). According to the latest Tourism Satellite Account report published by the National Institute of Statistics (NIS) in 2023, the direct share of tourism in aggregate GDP was 5%, accounting for approximately 2.3% of total employment ([NIS, 2024](#)). In revenue terms, inbound tourism receipts amounted to USD 2.23 billion; concurrently, domestic tourism expenditure totaled USD 4.7 billion in 2023, which likewise signals the breadth of tourism demand across market segments (Tunisian National Tourism Office, [TNTO, 2024](#)). Nevertheless, Mediterranean coastal destinations—including Tunisia—face mounting environmental pressures: the energy demand, water use, waste generation, and transport-related emissions associated with tourism drive negative externalities, while plastic pollution, beach erosion, and ecosystem stress intensify peak season risks and degrade destination quality. Consequently, policy and industry priorities are increasingly emphasizing circular practices, local renewable energy production, and the diffusion of green innovations ([Jipa et al., 2025](#); [Karimov et al., 2025](#)), providing pathways to reduce the sector’s ecological footprint and lower operational risks associated with energy price volatility. At the same time, foreign direct investment can mobilize capital and diffuse technologies that upgrade tourism supply ([Akhtar et al., 2024](#); [Arain et al., 2020](#)).

At present, tourism’s competitiveness depends not only on conventional factors, such as price competitiveness and transport access, but also—decisively—on sustainability ([World Economic Forum et al., 2024](#)). Moreover, environmental quality, the energy mix, technological capability, and the nature of foreign investment jointly shape demand and productivity. Most prior research—both in developed and developing economies—has conceptualized tourism primarily as an exogenous variable, typically employed to explain the evolution of economic growth or environmental quality ([Aydin, 2022](#); [Alqaralleh et al., 2025](#); [Balsalobre-Lorente et al., 2020](#); [Belabbas et al., 2025](#); [Dogru et al., 2020](#); [Liu et al., 2022](#); [Lv et al., 2022](#); [Radić, 2022](#); [Zaghdoud, 2025](#)). However, few studies have treated tourism development as an endogenous outcome shaped by its structural determinants. Among these rare contributions, [Hailiang et al. \(2023\)](#) and [Qamruzzaman \(2023\)](#) have highlighted how environmental quality and renewable energy consumption can directly and indirectly promote tourism development. Building on this emerging strand, the present study advances a more integrated perspective, positioning tourism development as the result of intertwined environmental, technological, and financial forces rather than a mere driver of macroeconomic or ecological change. Moreover, a clear regional gap persists. In North Africa—and in Tunisia specifically—country-level studies rarely combine environmental degradation, renewable energy, technological innovation, and foreign direct investment within one empirical model of tourism development. To our knowledge, no studies of this type have focused on Tunisia, despite the sector’s weight in jobs and foreign-currency earnings. Tunisia is a small, open economy in transition; thus, external shocks, capital inflows, and technology diffusion can reshape tourism performance. In this context, Tunisia appears to be a particularly relevant case for examining how sustainability-oriented transformation can unfold within a tourism-dependent Mediterranean economy. Tunisia offers a compelling single-country case. It is a recognized Mediterranean destination and, moreover, appears among the top recommended places to discover in 2026 as reported by [Lonely Planet \(2025\)](#). Yet, it faces structural transition pressures typical of the region: coastal vulnerability, environmental strain, and energy price exposure. At the same time, Tunisia

leads the African continent in renewable energy policy, access, and efficiency, according to the World Bank's Sustainable Energy Regulation Indicators ([World Bank Data, 2024](#)). Consequently, policy momentum in clean energy and digital upgrading creates a timely window to realign tourism with sustainability goals. Therefore, examining Tunisia now can yield targeted evidence on how a mid-sized, open economy can balance competitiveness, resilience, and ecological integrity under transition conditions.

Taken together, these two perspectives define both the conceptual and regional gaps that this study aims to close. Accordingly, this study advances beyond prior evidence. Instead, it extends the discussion to a country that has received limited empirical attention despite its strategic tourism sector. By integrating these dimensions within a coherent framework, this study builds a logical bridge between global theories and Tunisia's specific transition challenges. In line with these arguments, we develop an integrated time-series framework for Tunisia (1990–2023) in which tourism development (TD) is modeled as a joint outcome of environmental degradation (ED), renewable energy usage (RE), technological innovation (TI), and foreign direct investment (FDI). We test for a long-run equilibrium, estimate short-run adjustment dynamics using ARDL bounds, and confirm long-run coefficients with Fully Modified Ordinary Least Squares (FMOLS), thereby ensuring robust identification of both equilibrium and adjustment processes.

Conceptually, this study contributes to the theoretical understanding of sustainable tourism by advancing a unified framework in which environmental degradation (ED), renewable energy (RE), technological innovation (TI), and foreign direct investment (FDI) interact as mutually reinforcing pillars of Tunisia's sustainability transition. Based on the Environmental Kuznets Curve ([Kuznets, 1955](#); [Dinda, 2004](#)) and destination-quality logic ([Hassan, 2000](#)), lower environmental degradation enhances long-term destination appeal. Moreover, under energy-transition theory ([Sovacool, 2016](#)), renewable energy supports competitiveness by reducing pollution and energy-price volatility. Similarly, within endogenous growth theory ([Romer, 1990](#)) and the Schumpeterian innovation perspective ([Schumpeter, 1934](#); [Aghion & Howitt, 1992](#)), technological innovation improves efficiency, diversity, and service quality, thereby amplifying the benefits of clean energy and environmental management. In the same way, consistent with the Ownership–Location–Internalization (OLI) Paradigm of international production ([Dunning, 1988](#)), foreign direct investment channels capital, know-how, and standards that accelerate the diffusion of green technologies and digital tools. Within Tunisia's structural transformation, these four forces are deeply interdependent: renewable energy and innovation jointly offset environmental degradation, while FDI magnifies both through capital deepening and knowledge spillovers. Consequently, tourism development emerges as an endogenous outcome of the broader sustainability transition rather than an external driver of growth or environmental stress. This theoretical synthesis constitutes the main conceptual novelty of the study and clearly distinguishes it from earlier works that examined each determinant in isolation.

In line with these theoretical arguments, the empirical investigation is structured around the following objectives:

- (i) Quantify the long-run elasticities and identify the short-run adjustment speeds between TD and its determinants (ED, RE, TI, and FDI), thereby revealing when the effects materialize.
- (ii) Explain the expected signs via established mechanisms—the destination-quality and Environmental Kuznets logic for ED, credibility and cost stability for RE, Schumpeterian efficiency gains for TI, and Ownership–Location–Internalization spillovers for FDI—thus ensuring theory-consistent inference.
- (iii) Uncover country-specific complementarities and trade-offs among ED, RE, TI, and FDI that single-factor designs omit.

- (iv) Translate the estimated elasticities and adjustment speeds into sequenced and actionable policy guidance for Tunisia's sustainability transition.

To meet these objectives, the analysis employs annual Tunisian data, with TD proxied by international tourism receipts in constant prices, ED measured by total greenhouse gas emissions, RE defined as the share of renewables in aggregate final energy consumption, TI captured by patent applications, and FDI measured by net inflows relative to GDP; all series are compiled from the World Development Indicators ([World Bank, 2024](#)) and cover the period from 1990 to 2023. Methodologically, this study employs the Autoregressive Distributed Lag (ARDL) bounds testing approach to investigate the cointegrated relationship and dynamic adjustment, and then cross-validates the long-run relation using Fully Modified Ordinary Least Squares (FMOLS), thereby providing a complementary estimator for the cointegrating vector.

The remainder of this paper is structured as follows: Section 2 surveys the pertinent international literature on the tourism, environment, energy, innovation, and investment nexus, then presents the research gap addressed by this study. Section 3 describes the methodological approach, including the data, empirical model, and econometric strategy based on the ARDL bounds testing framework. Section 4 presents empirical findings and a discussion, including diagnostic checks, stability analysis, and a robustness test using the FMOLS technique. In Section 5, the paper concludes with policy implications and outlines avenues for future research that are consistent with the study's scope and design.

2. Literature Review

Research on tourism development increasingly situates the sector within the sustainability transition. Environmental quality, the energy mix, technological capability, and foreign direct investment shape destination appeal, productivity, and resilience. Nevertheless, reported effects vary by context, method, and horizon. The existing literature has mostly focused on the direct impacts of tourism development, either treating it as the cause of economic development or the source of environmental pressure ([Chaudhary et al., 2025](#); [Halkos & Ekonomou, 2023](#); [Liu et al., 2022](#); [Prasad et al., 2024](#); [Teng et al., 2021](#)). However, there is still a major gap: how wider economic and ecological forces affect tourism sustainability is greatly underexplored. Recent policy agendas, therefore, call for assessments that consider the influence of environmental degradation, renewable energy use, green innovation, and foreign direct investment on tourism outcomes, especially in economies that are in the process of structural transformation ([J. Guo & Cai, 2022](#); [Peng et al., 2025](#)). Neglecting to address these interactions may result in distorted trade-offs in policies and the formulation of erroneous prescriptions. Therefore, before stating formal econometric expectations, it is necessary to provide a brief synthesis to clarify the joint and dynamic relationships between these determinants and tourism development.

2.1. Environment–Tourism Nexus

Research into the nexus between tourism growth and environmental damage (particularly through greenhouse gas emissions) has yielded varied outcomes, often influenced by geographic, economic, and methodological differences ([Pinto et al., 2025](#)). On the one hand, tourism is usually mentioned as a major factor leading to environmental damage. For instance, [Gulistan et al. \(2020\)](#) used panel data of 112 countries and found that the activities of tourism significantly increase the degradation of the environment through high levels of CO₂ emissions. The result was consistent in different income categories, which confirmed that tourism is a significant environmental threat that requires specific mitigation strategies. Similarly, [Ren et al. \(2019\)](#) employed panel ARDL and quantile regression techniques on data from 1995 to 2014 across Mediterranean countries, including the North African nations

of Egypt, Morocco, and Tunisia, documenting that the income level of tourist arrivals increases environmental pollution at lower quantiles, while at higher quantiles, it contributes to lower emissions, indicating a varying environmental impact depending on the quality of tourism flows. In a related study, Kwakwa (2024) applied regression analysis to data from 1995 to 2021 across seven African countries, including Egypt, Morocco, Tunisia, and Algeria, showing that while natural resources and financial development enhance international tourism demand, higher carbon dioxide emissions reduce it, suggesting that environmental degradation may deter tourism rather than result from it. There exist contexts in which tourism either exerts positive environmental externalities or its initial negative impacts diminish over time due to sustainable management practices and effective policy interventions. Liu et al. (2022), using spatial econometrics on panel data from 70 countries, discovered that tourism development directly increases CO₂ emissions but also indirectly contributes significantly to emission reductions through spatial spillover effects, ultimately resulting in a net beneficial environmental impact. These findings support the inverted-U-shaped hypothesis (Environmental Kuznets Curve), where emissions initially rise with tourism growth but decrease beyond a critical development threshold due to increased environmental awareness, improved infrastructure, and increased education expenditure. Consistent with this perspective, Ahmad et al. (2019) investigated lower-middle-income Southeast Asian countries using Fully Modified Ordinary Least Squares, reporting country-specific effects. Notably, tourism deteriorated environmental quality in Indonesia and the Philippines, but improved environmental conditions in Vietnam through proactive policy frameworks and sustainable practices.

Overall, the literature suggests that tourism's environmental effects depend on a country's stage of development and the strength of its environmental policies. Based on the Environmental Kuznets Curve (Kuznets, 1955; Dinda, 2004) and the destination quality logic (Hassan, 2000), it is expected that higher environmental degradation initially accompanies tourism growth but ultimately constrains long-term development as destination quality declines.

H1: *Environmental degradation has a negative long-run effect on tourism development in Tunisia.*

2.2. Energy–Tourism Nexus

The connection between tourism development and renewable energy consumption has increasingly garnered scholarly attention, highlighting the crucial role of renewable energy in sustainable tourism (Roucham & Zaghdoud, 2025; Taušová et al., 2025). Several proponents argue that increasing reliance on renewable energy sources enables tourism industries to align with climate goals and attract environmentally conscious travelers. In this regard, Salahodjaev et al. (2022) employed a two-step GMM estimator on a panel of European and Central Asian countries (1990–2015). They concluded that tourism contributes to the rise in CO₂ emissions, but renewable energy greatly overcomes this aspect. They concluded that a 10-percentage-point rise in the production of renewable electricity will lower per capita emissions by around 4.1 percent, thereby supporting the Environmental Kuznets Curve (EKC) hypothesis and indicating that more environmentally friendly energy policies can help make tourism more sustainable. Similarly, Aziz and Sarwar (2023) used the updated STIRPAT model with advanced panel data methods to test the ecological footprint of MENA countries between 1996 and 2020. They found out that tourism, economic growth, and urbanization are major causes of environmental degradation in the region. Nevertheless, their research also established that the adoption of renewable energy is very important in reducing such adverse environmental impacts. The authors suggest that policymakers should amend legislative frameworks so as to promote local and foreign investments in renewable energy, ensuring a shift to ensure that tourism development is

in tandem with environmental sustainability in the region. In the same vein, [Abdullayev et al. \(2023\)](#) carried out a case-based study of urban sustainability projects in the North Africa region, concentrating on Moroccan and Egyptian initiatives. They revealed that the incorporation of renewable energy and especially solar and wind, into urban planning not only decreases the environmental impact but also increases the resilience and appeal of tourism-driven cities in terms of energy security and ecological sustainability in a wide variety of urban settings. In order to investigate the effect of renewable energy on the development of tourism in Malaysia, [Qamruzzaman \(2023\)](#) used econometric estimation to test the empirical relationship of the ARDL bound test, the Bayer–Hanckel cointegration test, and the nonlinear ARDL test, covering the time frame between 1990 and 2021. His empirical findings revealed that the implementation of renewable energy reduces the operating expenses of tourism, which reinforces margins and contributes to sustainability in the long term.

The literature under review places a consistent emphasis on renewable energy as one of the leading facilitators of sustainable tourism, reduction in emissions, increased energy efficiency, and destination credibility. Guided by energy transition theory ([Sovacool, 2016](#)) and supported by recent empirical evidence ([Aydin, 2022](#); [Qamruzzaman, 2023](#)), renewable energy is expected to foster sustainable tourism growth.

H2: *Renewable energy use has a positive long-run effect on tourism development in Tunisia.*

2.3. Innovations–Tourism Nexus

Green innovations, encompassing environmental patents and eco-technologies, have been recognized as potential facilitators of sustainable tourism; however, empirical evidence remains heterogeneous ([Chau et al., 2023](#); [Mahadevan & Suardi, 2025](#)). Emerging research consistently emphasizes that the adoption of ecological technologies and environmentally friendly innovations can play a pivotal role in promoting low-carbon tourism and reducing the ecological footprint of the tourism sector. In this regard, [Lv et al. \(2022\)](#) applied the Quantile Autoregressive Distributed Lag (QARDL) approach on Chinese regional data spanning 2000–2019 to examine the impact of tourism and green technological innovations on ecological sustainability. Their findings confirmed that, both in the short and long run, eco-innovation coupled with tourism can effectively reduce ecological degradation, particularly by lowering the ecological footprint across various quantiles. Interestingly, their study also suggested that financial development and economic expansion alone lacked a sustainability dimension, implying that green innovation is essential to mitigate tourism’s environmental trade-offs. Similarly, [Cheng and Ren \(2024\)](#) conducted an OLS-based panel study on the Yangtze River Delta in China to investigate how ecological technological innovation enhances the tourism economy. Their study revealed a strong mediating role of industrial structure upgrades, indicating that green technological advancements directly boost tourism productivity and indirectly promote eco-tourism by restructuring the tourism industry itself. For Mediterranean North Africa, [Amer et al. \(2024\)](#) conducted qualitative research on 5-star hotels in Hurghada, Egypt, demonstrating that the adoption of green technologies, such as solar panels, motion-sensor lighting, and water-saving systems, enhances sustainable tourism development by reducing resource consumption and operational costs while meeting the expectations of environmentally conscious tourists across various markets. Their study also found that green certifications and eco-labels play a crucial role in enhancing the attractiveness of destinations for environmentally conscious travelers.

The literature indicates that green technological innovation enhances efficiency, supports eco-certification, and strengthens competitiveness. Drawing on endogenous growth theory ([Romer, 1990](#)) and the Schumpeterian innovation perspective ([Schumpeter, 1934](#);

[Aghion & Howitt, 1992](#)), technological innovation is expected to improve tourism performance by enabling cleaner and more diversified services.

H3: *Technological innovation has a positive long-run effect on tourism development in Tunisia.*

2.4. FDI–Tourism Nexus

Foreign direct investment can support tourism through capital, standards, and technology spillovers. Multinational firms bring finance, managerial know-how, and digital tools; therefore, hotels and related services can be upgraded. Under the Ownership–Location–Internalization paradigm, internalized operations also help maintain consistency in quality and environmental practices ([Dunning, 1988](#)).

[Adeola et al. \(2020\)](#) analyzed panel data from forty-four African countries, including Morocco, Tunisia, Algeria, and Egypt. They employed a panel ARDL approach and revealed a bidirectional long-run relationship between foreign direct investment and tourism development. Consequently, FDI not only promotes tourism but also responds to its growth. Similarly, [Soumaré \(2015\)](#) focused on the same North African countries and found that FDI is significantly associated with welfare improvements. In particular, tourism was identified as one of the main sectors attracting investment. [Arain et al. \(2020\)](#) utilized monthly data and a quantile-on-quantile approach for leading destinations, documenting that inbound tourism increases FDI across most of the distribution. However, the effects weaken at lower and middle quantiles for some cases (e.g., Mexico and Russia), which underscores heterogeneity. [Gopalan et al. \(2024\)](#) examined bilateral Greenfield FDI from 2003 to 2017 and found that higher bilateral FDI stimulates tourism flows, especially between linguistically or geographically distant partners, consistent with market access and signaling channels.

The reviewed evidence indicates that foreign direct investment may be a source of capital, managerial expertise and technology spillovers that improve the capacity and quality of tourism. In line with the Ownership–Location–Internalization (OLI) paradigm ([Dunning, 1988](#)), FDI is projected to contribute to the growth of tourism via financial deepening and the transfer of knowledge.

Although most studies report a positive contribution of FDI to the tourism industry, emerging evidence suggests that its effects may be heterogeneous. In some contexts, weak institutional capacity, limited local participation, or environmentally intensive investment can reduce FDI's net benefits for the tourism sector ([Yang et al., 2021](#); [Sokhanvar, 2019](#)). Conversely, countries with strong regulatory frameworks and technological absorptive capacity tend to capture greater spillovers and sustainability gains. This study implicitly accounts for such heterogeneity by modeling FDI jointly with renewable energy and technological innovation, thereby allowing the estimation to reflect complementarity effects rather than assuming uniform outcomes.

H4: *Foreign direct investment has a positive long-run effect on tourism development in Tunisia.*

2.5. Research Gap

Our review of the existing literature reveals an extensive body of empirical studies that link tourism with environmental quality and selected economic variables. However, most studies conceptualize tourism primarily as an exogenous driver of growth or environmental pressure; consequently, they overlook the endogenous determination of tourism by external structural forces. Conceptually, the literature rarely models how environmental degradation, renewable energy use, technological innovation, and foreign direct investment jointly shape tourism development. Methodologically, single-factor designs and isolated estimators limit the detection of complementarities, trade-offs, and dynamic adjustment. Empirically, a single-country, multi-determinant, lagged, time-series framework distin-

guishing between long-run equilibria and short-run adjustments does not exist for North Africa—particularly Tunisia—despite the ongoing structural adjustment in small, open, developing economies.

To address these gaps, this study estimates an integrated model for Tunisia (1990–2023) using the Autoregressive Distributed Lag (ARDL) bounds approach and confirms long-run coefficients with Fully Modified Ordinary Least Squares (FMOLS). This design recovers both the long-run relationship between tourism development and its structural determinants and the short-run speed of adjustment. Recent advances in sustainability analytics emphasize the potential of data science methods to uncover complex linkages among environmental, financial, and technological variables (Chen, 2024), complementing conventional econometric techniques such as those applied in this study. Consequently, it provides context-specific elasticities and sequenced, policy-relevant guidance that is directly applicable to sustainability-oriented tourism strategies in the region.

Based on the theoretical foundation and empirical evidence reviewed above, this study proposes an integrated conceptual framework in Figure 1 that synthesizes the hypothesized relationships between environmental degradation, renewable energy, technological innovation, foreign direct investment, and tourism development within Tunisia’s sustainability transition. The positive effects are indicated by (+) arrows, while negative effects are indicated by (−) arrows. FDI positively influences TD both directly and indirectly through RE and TI (dash arrows). The framework emphasizes that tourism development (TD) is the endogenous outcome of the interaction between interrelated environmental, technological and financial dynamics in the context of Tunisia’s sustainability transition.

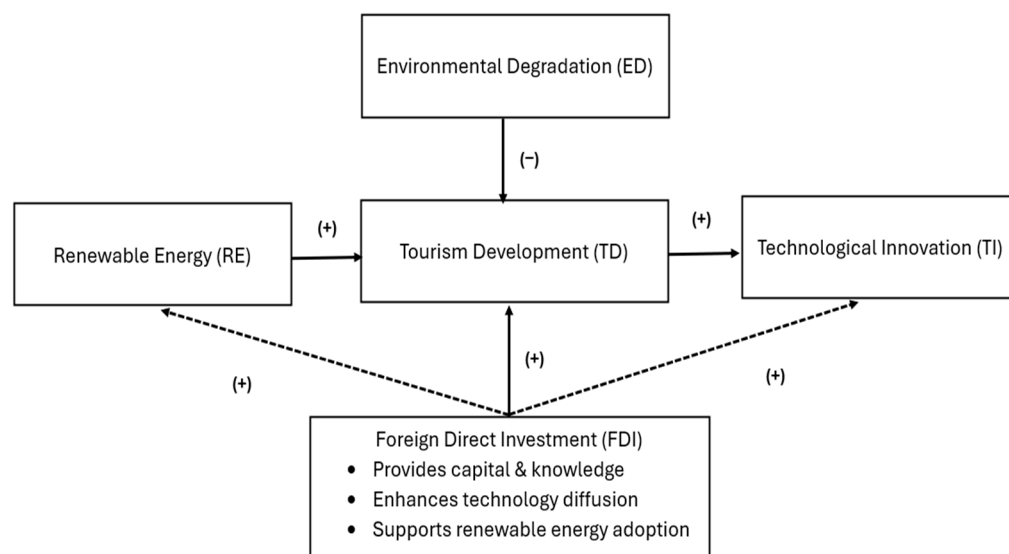


Figure 1. Conceptual Framework of the Tourism–Environment–Energy–Innovation–FDI Nexus.

3. Methodological Approach

3.1. Conceptual Model

Building on the theoretical and empirical discussions presented earlier, this study empirically operationalizes tourism development (TD) as an endogenous outcome determined by environmental degradation (ED), renewable energy (RE), technological innovation (TI), and foreign direct investment (FDI). According to the Environmental Kuznets Curve (Kuznets, 1955; Dinda, 2004) and destination-quality logic (Hassan, 2000), environmental degradation is expected to exert a negative long-run effect on TD, as deteriorating ecosystems reduce the attractiveness of destinations. Conversely, energy-transition theory (Sovacool, 2016) suggests that renewable energy enhances competitiveness by sta-

bilizing costs, reducing emissions, and improving environmental credibility. Likewise, endogenous growth theory (Romer, 1990) and the Schumpeterian innovation perspective (Schumpeter, 1934; Aghion & Howitt, 1992) imply that technological innovation raises efficiency and service quality, thereby fostering sustainable tourism growth. Moreover, the Ownership–Location–Internalization (OLI) paradigm (Dunning, 1988) indicates that FDI contributes both directly through capital and knowledge transfers and indirectly by facilitating renewable-energy and innovation diffusion. Hence, the causal direction flows from ED, RE, TI, and FDI toward TD. This theoretical structure forms the empirical basis for the model estimated through the ARDL bounds testing and FMOLS approaches, which capture both long-run equilibrium and short-run adjustments within Tunisia’s sustainability transition.

3.2. Data

This study empirically examines the long- and short-term impacts of environmental degradation, renewable energy utilization, technological innovation, and foreign direct investment on the sustainable development of the tourism sector in Tunisia. For this objective, we employ a time series analysis and an Autoregressive Distributed Lag (ARDL) bound test cointegration approach (Pesaran et al., 2001). This investigation uses a dataset that is composed of yearly time series observations from 1990 to 2023. This time frame was chosen considering the consistency of available data for all the variables that we want to relate to the case of Tunisia. All data were recovered according to the World Bank’s World Development Indicators (World Bank, 2024), which provide comparability as well as international reliability. To enhance the robustness of the empirical analysis, all the variables have been log-transformed to linearize the relationships, normalize the distributions, and reduce heteroskedasticity. Tourism development, the dependent variable, is proxied by international tourism receipts in constant USD of 2015. This proxy is selected because of its capacity to reflect the actual inflation-adjusted economic value of inbound tourism. Unlike arrival counts, which can only identify the numbers of visitors, tourism receipts provide a more meaningful measure of the economic impact and sustainability of tourism. To assess environmental degradation, we use total emissions of greenhouse gases, measured in million metric tons of CO₂-equivalent (Mte CO₂). This indicator is a summation of all primary greenhouse gases with reference to their global warming potential, and therefore is a more comprehensive and policy-relevant measure compared to CO₂ emissions. Renewable energy consumption is expressed as a percentage of the final total energy consumption. This variable captures the structural changing trend moving towards cleaner forms of energy supply and their potential impact on sustainable tourism. Patent applications by resident and non-resident inventors are used as a proxy for technological innovation, capturing the overall environmental innovation relevant to eco-tourism development and green practices. Patent applications are a standard proxy in innovation and sustainability research. They capture the creation and diffusion of new technologies across sectors—energy efficiency, digital services, and environmental management—and thus directly affect destination quality and productivity. Moreover, unlike narrower indices of information and communications technology (ICT) adoption or research and development (R&D) expenditures, patent counts reflect both domestic inventive activity and international technology transfer. Thus, they provide a comprehensive measure of innovation intensity pertinent to Tunisia’s tourism transition. Finally, foreign direct investment is captured through net inflows as a percentage of GDP, reflecting the extent to which international capital supports the expansion and modernization of the tourism sector. All FDI values for Tunisia during the study period 1990–2023 are positive, according to World Development

Indicators (World Bank, 2024). Therefore, the logarithmic transformation is well defined for the entire sample, and no data adjustment or constant-shift correction was necessary.

This dataset is a powerful tool for exploring the highly interrelated dynamics between tourism development and its environmental, technological, and financial determinants for the broader sustainable development-related context of Tunisia's trajectory. Table 1 provides a description of the variable definitions, units of measurement, and data sources used in this study.

Table 1. Specification of variables, definitions, units, and sources.

Variables	Description	Measurement Units	Sources
TD	Tourism development	International tourism, receipts (2015 Constant US\$)	World Bank (2024)
ED	Environmental degradation	Total emissions of greenhouse gases, expressed as million metric tons of CO ₂ -equivalent (Mt CO ₂ e)	World Bank (2024)
RE	Renewable energy usage	Percentage of total final energy consumption	World Bank (2024)
TI	Technological innovations	Number of patent applications	World Bank (2024)
FDI	Foreign direct investment	Net inflows of FDI as a percentage of GDP	World Bank (2024)

Table 2 presents the key statistical overview of the variables used in the analysis, offering a more in-depth understanding of their distributional properties. The dependent variable LnTD (log of tourism development) has skewness of 0.59 and kurtosis of 2.84, indicating a rather symmetric distribution with tails not far from normal. The Jarque–Bera (JB) test gives a probability value of 0.124, which means that there is no significant evidence against this assumption. LnED (log of environmental degradation) shows moderate negative skewness (−0.52), kurtosis of 1.87, and a JB probability of 0.189, which also represents approximate normality. The distribution of LnRE (log of renewable energy consumption) is also fairly well-behaved, with a slight negative skew (−0.36), kurtosis of 2.33, and a JB *p*-value of 0.509. For LnTI (log of technological innovation), the skewness is −0.23 and the kurtosis is 1.69; the corresponding JB probability of 0.257 does not indicate any significant deviation from normality. Lastly, LnFDI (log of foreign direct investment) is marginally right-skewed (0.30) and slightly leptokurtic (kurtosis = 3.52), yet the JB probability of 0.645 confirms its compatibility with a normal distribution. Overall, the descriptive results suggest that the distributions of all variables are sufficiently close to normal, thereby supporting their suitability for inclusion in the ARDL modeling framework.

Table 2. Descriptive Overview of Model Variables.

Variables in Logarithmic Forms	LnTD	LnED	LnRE	LnTI	LnFDI
Mean	21.55690	3.538382	2.610162	5.707342	0.759683
Median	21.40560	3.601534	2.649708	5.783025	0.714086
Maximum	23.86418	3.774564	2.778819	6.522093	2.243337
Minimum	20.73024	3.145001	2.451005	4.634729	−0.462180
Std. Dev.	0.513449	0.197455	0.078081	0.579909	0.544713
Skewness	0.588034	−0.521628	−0.355677	−0.227828	0.297188
Kurtosis	2.83704	1.874589	2.331878	1.691258	3.516501
Jarque–Bera	5.64174	3.336157	1.349251	2.720605	0.878414
Probability	0.123607	0.188609	0.509347	0.256583	0.644547
Sum	732.9347	120.3050	88.74551	194.0496	25.82923
Sum Sq. Dev.	8.699792	1.286624	0.201187	11.09773	9.791516
Observations	34	34	34	34	34

3.3. Empirical Model

To evaluate the factors of sustainable tourism development in Tunisia, an empirical model is built in this study that reflects the dynamic dependency relationship between tourism receipts and explanatory variables: environmental degradation, renewable energy consumption, technological innovation, and foreign direct investment. Based on the theoretical and empirical literature, the model framework captures the dynamics of environmental and economic factors affecting tourism performance over time. The initial mathematical model statement is given by the following:

$$TD_t = f(ED_t, RE_t, TI_t, FDI_t) \quad (1)$$

where TD_t denotes tourism development, ED_t represents environmental degradation, RE_t stands for renewable energy use, TI_t is technological innovations and FDI_t is foreign direct investment, with (t) being the time.

The baseline mathematical model can be converted into a basic econometric equation under its log-linear form:

$$\ln TD_t = \alpha_0 + \alpha_1 \ln ED_t + \alpha_2 \ln RE_t + \alpha_3 \ln TI_t + \alpha_4 \ln FDI_t + \varepsilon_t \quad (2)$$

Based on prior theoretical and empirical studies, environmental degradation is expected to affect tourism development negatively, implying that $\alpha_1 = \frac{\partial \ln TD}{\partial \ln ED} < 0$. Conversely, the use of renewable energy, technological innovation, and foreign direct investment is expected to encourage tourism development, implying that $\alpha_2 = \frac{\partial \ln TD}{\partial \ln RE} > 0$, $\alpha_3 = \frac{\partial \ln TD}{\partial \ln TI} > 0$, and $\alpha_4 = \frac{\partial \ln TD}{\partial \ln FDI} > 0$.

Even though other additional variables like exchange rate stability, infrastructure quality, or institutional factors can actively affect tourism performance, they would significantly decrease the degrees of freedom of the model in a small sample. Thus, the model focuses on the four most pertinent structural determinants of sustainability transition: environmental degradation, renewable energy, and foreign direct investment. These omitted dimensions are partially reflected by the variables included, as FDI and innovation tend to reflect institutional and infrastructural impacts. Once a longer time series is available, future work might extend the framework to include institutional and demand-side indicators to reflect more macroeconomic impacts.

3.4. Econometric Strategy

This study uses the Autoregressive Distributed Lag (ARDL) bounds testing approach (Pesaran & Shin, 1998; Pesaran et al., 2001) to test the dynamic relationship between tourism development and the principal determinants of tourism development, which are environmental degradation, renewable energy consumption, technological innovation, and foreign direct investment, during the period of 1990 to 2023. The choice of the ARDL methodology is based on its three advantages. First, it is particularly appropriate for small sample sizes, as in our study (34 annual observations), because it guarantees robust hypothesis testing based on the standard normal asymptotic distribution. Second, it offers high flexibility in incorporating regressors with mixed integration properties, either stationary at level $I(0)$ or integrated at first difference, without the need for preliminary unit root order testing beyond ensuring that none are integrated at $I(2)$. Third, the ARDL approach not only avoids the problems of residual serial correlation but also offers consistent estimations in the presence of the endogeneity problem by reordering an appropriate lag structure. Compared with other methods, ARDL is better suited to this setting. Johansen cointegration typically requires larger samples and variables of the same integration order, whereas ARDL accommodates mixed $I(0)/I(1)$ processes and remains efficient in small samples.

Likewise, FMOLS/DOLS focus on long-run coefficients conditional on cointegration and do not recover short-run adjustments, while ARDL delivers both within a single-equation error correction form without the complexity of multi-equation VAR/VECM systems. Overall, the ARDL approach provides a robust framework for capturing long-run equilibria and short-run adjustments in the tourism–environment–innovation nexus, making it well suited for policy analysis in emerging economies such as Tunisia.

Based on Equation (2), the ARDL-bound test model structure is expressed as follows:

$$\Delta \ln TD_t = \lambda_0 + \lambda_1 \ln TD_{t-1} + \lambda_2 \ln ED_{t-1} + \lambda_3 \ln RE_{t-1} + \lambda_4 \ln TI_{t-1} + \lambda_5 \ln FDI_{t-1} + \sum_{i=1}^p \beta_{1i} \Delta \ln TD_{t-i} + \sum_{i=0}^{q_1} \beta_{2i} \Delta \ln ED_{t-i} + \sum_{i=0}^{q_2} \beta_{3i} \Delta \ln RE_{t-i} + \sum_{i=0}^{q_3} \beta_{4i} \Delta \ln TI_{t-i} + \sum_{i=0}^{q_4} \beta_{5i} \Delta \ln FDI_{t-i} + \varepsilon_t \quad (3)$$

where Δ represents the first difference operator; $\lambda_1, \lambda_2, \lambda_3, \lambda_4$, and λ_5 refer to the long-run coefficient, and $\beta_{1i}, \beta_{2j}, \beta_{3h}, \beta_{4k}$, and β_{5l} denote the short-run dynamics. The coefficients, p, q_1, q_2, q_3 , and q_4 are the number of lags associated with each variable in the first difference. We employed the Akaike Information Criteria (AIC) method to select the optimal lag numbers.

The initial stage of the econometric approach centers on identifying the integration order of the model's variables through stationarity testing. This step is necessary for the proper use of the ARDL bounds testing framework, which requires the variables of interest to be integrated to order zero, $I(0)$, order one, $I(1)$, or a combination of the two, but clearly excluding variables integrated to order two, $I(2)$. For this purpose, the study applies three well-known unit root tests: Augmented Dickey–Fuller (ADF, [Dickey & Fuller, 1979](#)), Phillips–Perron (PP, [Phillips & Perron, 1988](#)), and Dickey–Fuller GLS (DF-GLS) by [Elliott et al. \(1996\)](#). The use of more than one test ensures the robustness of the results because each test has varied sensitivity to sample characteristics such as size, autocorrelation, and possible structural breaks in the data. These tests are applied not only to the variables in their original form, but also to their first differences, which helps us to find the exact point of stationarity. Proper identification of the integration order is important for preventing misleading inferences and for obtaining a reliable outcome of the ARDL model in terms of the transitory dynamics and the long-run equilibrium relations among the variables considered.

Once the integration conditions are satisfied, the ARDL bounds test ([Pesaran et al., 2001](#)) is applied to investigate the existence of a long-run equilibrium connection among the variables. This step is carried out by computing an F-statistic for the joint significance of the lagged level variables in Equation (3), i.e., $\begin{cases} H_0 : \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0 \\ H_1 : \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq 0 \end{cases}$ and comparing it against critical bounds (i.e., $I(0)$ and $I(1)$). If the F-statistic is above the upper bound (i.e., $I(1)$), the null hypothesis H_0 (absence of cointegration) can be rejected. In other terms, there is a cointegration relationship between the variables. However, if the F-statistic is below the lower bound (i.e., $I(0)$), this implies there is no cointegration relationship. If the value falls between the bounds, the result is inconclusive.

Upon confirming the presence of cointegration, the ARDL model is estimated in two stages. In the first stage, we extract the long-run coefficients (i.e., $\lambda_1, \lambda_2, \lambda_3, \lambda_4$, and λ_5) from the estimated equation, Equation (3). Then, in the second stage, to estimate the short-run coefficients, we reparametrize the ARDL model given by Equation (3) into its corresponding unrestricted error correction model (ECM) that captures the short-run adjustments toward the long-run equilibrium, as shown by the following equation:

$$\Delta \ln TD_t = \mu_0 + \sum_{i=1}^p \mu_{1i} \Delta \ln TD_{t-i} + \sum_{j=0}^{q_1} \mu_{2j} \Delta \ln ED_{t-j} + \sum_{h=0}^{q_2} \mu_{3h} \Delta \ln RE_{t-h} + \sum_{k=0}^{q_3} \mu_{4k} \Delta \ln TI_{t-k} + \sum_{l=0}^{q_4} \mu_{5l} \Delta \ln FDI_{t-l} + \theta ECT_{t-1} + \varepsilon_t \quad (4)$$

where μ_{1i} , μ_{2j} , μ_{3h} , and μ_{4k} are the short-run dynamic coefficients, and θ denotes the adjustment coefficient of the error-correction term (ECT_{t-1}), capturing the speed of convergence to the long-run equilibrium following a temporary shock. A negative and significant θ indicates convergence toward long-run equilibrium, confirming stability and the presence of a meaningful adjustment process.

Finally, the robustness of the model is evaluated based on a set of diagnostic tests, including serial correlation, heteroskedasticity, residual normality, and specification validity. Moreover, the stability of the estimated parameters is evaluated using the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) procedures, as well as the FMOLS robustness technique. These procedures validate whether the estimated parameters remain consistent over the study period and whether the model's structure is stable over time.

4. Empirical Findings and Discussion

4.1. Stationarity

To verify the robustness of the econometric analysis and the appropriateness of the chosen estimation method, we first conducted unit root tests using the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Dickey–Fuller Generalized Least Squares (DF-GLS) approaches. These tests were applied to the level and first-differenced logarithmic forms of the variables under both constant and trend specifications. As Table 3 shows, the test statistics indicate that the variables exhibit mixed orders of integration, with some being stationary at the level and others at the first difference. Specifically, the variable representing foreign direct investment ($\ln FDI$) is consistently found to be stationary at the level across all three tests and both specifications at the 1% level of significance, indicating that $\ln FDI$ is an integrated of order zero, $I(0)$. Meanwhile, the remaining variables—tourism development ($\ln TD$), environmental degradation ($\ln ED$), renewable energy ($\ln RE$), and technological innovation ($\ln TI$)—appear non-stationary at the level, as their test statistics generally fail to exceed the critical values required for rejecting the null hypothesis of a unit root. However, upon first difference, all these variables become stationary at the 1% or 5% significance level in nearly all tests and specifications. For instance, the first-differenced values of $\ln TD$ and $\ln RE$ display strong stationarity, as reflected by the significantly negative test statistics in both ADF and PP tests. Similarly, the differenced series of $\ln ED$, $\ln TI$, and $\ln FDI$ are stationary, as the null hypothesis of a unit root is rejected under conventional significance thresholds, confirming their $I(1)$ behavior. Given these outcomes, which indicate a mixture of $I(0)$ and $I(1)$ series and the absence of $I(2)$ integration, it is methodologically valid to proceed with the ARDL estimation technique. The fact that the ARDL approach is flexible enough to accommodate regressors of various integration orders without testing for cointegration beforehand makes it particularly appropriate for our data. This method enables us to identify the dynamic association between the examined variables and draw policy-relevant conclusions on how to develop the Tunisian tourism sector sustainably.

Table 3. Unit root tests.

Variables	ADF		PP		DF-GLS	
	Constant	Constant and Trend	Constant	Constant and Trend	Constant	Constant and Trend
$\ln TD$	−2.858	−3.168	0.093	0.215	−0.148	−0.587
$\ln ED$	−2.425	−0.793	−2.623 *	−1.401	0.183	−1.434
$\ln RE$	−1.429	−2.481	−1.941	−3.163 *	−1.257	−2.505
$\ln TI$	−2.158	−2.228	−1.489	−1.554	−1.815	−2.452

Table 3. Cont.

Variables	ADF		PP		DF-GLS	
	Constant	Constant and Trend	Constant	Constant and Trend	Constant	Constant and Trend
<i>ln FDI</i>	−4.388 ***	−4.404 ***	−4.396 ***	−4.384 ***	−1.997 **	−2.735 **
$\Delta \ln TD$	−5.373 ***	−4.879 ***	−3.781 **	−4.018 **	−2.539 **	−2.899 *
$\Delta \ln ED$	−7.162 ***	−7.962 ***	−7.145 ***	−10.444 ***	−2.811 ***	−8.146 ***
$\Delta \ln RE$	−8.795 ***	−8.645 ***	−11.206 ***	−10.381 ***	−8.439 ***	−8.851 ***
$\Delta \ln TI$	−4.389 ***	−4.576 ***	−3.464 **	−3.637 **	−3.344 ***	−4.301 ***
$\Delta \ln FDI$	−8.035 ***	−8.093 ***	−11.991 ***	−20.314 ***	−7.577 ***	−8.297 ***

Note: ΔX denotes the first-difference transformation of variable X. Rejection of the unit-root null is coded by (***), (**), and (*), denoting the 1%, 5%, and 10% significance thresholds, respectively.

4.2. ARDL Bound Test Cointegration

The findings presented in Table 4 clearly indicate the existence of a long-term equilibrium connection among the variables. The estimated F-statistic is 9.047838, which is substantially greater than the critical values of the upper bounds at all conventional significance levels, namely 3.52 at 10%, 4.01 at 5%, and 5.06 at 1%. Because the test statistic exceeds even the strict 1% threshold, the no-cointegration null hypothesis is decisively rejected. This outcome confirms that tourism development, environmental degradation, renewable energy consumption, technological innovation, and foreign direct investment are not independent of each other in the long term but instead move together stably. Although short-run fluctuations may occur due to shocks or policy changes, the presence of cointegration implies that such deviations are temporary and that the system consistently adjusts back toward equilibrium. Therefore, the variables are bound by a common stochastic trend, which provides strong justification for continuing to estimate long-term coefficients and for employing the corresponding error-correction model to capture both equilibrium dynamics and the adjustment process. Furthermore, this finding demonstrates the appropriateness of the ARDL approach as a methodological framework that allows us to study the impact of energy use, environmental pressures, technological innovation, and international investment as a whole on the sustainability of tourism development in Tunisia.

Table 4. Bounds test cointegration.

F-Statistic Bounds Test		Null Hypothesis: No Cointegrating Relationships Exist		
Test Statistics	Value	Significant Level	Lower Bounds I(0)	Upper Bounds I(1)
F-statistics	9.047838	10%	2.45	3.52
K	4	5%	2.86	4.01
		1%	3.74	5.06

4.3. ARDL Estimations

Table 5 indicates that ARDL estimates give a vivid difference between long-run equilibrium and short-run adjustment, and the log-log form enables the direct reading of the elasticities. Environmental degradation (ED) lowers tourism development (TD) in the long term: the elasticity of $\ln ED = -0.725$ ($p = 0.078$), which implies that a 1% increase in ED would be linked to a 0.73% decrease in TD; the impact is negative and statistically significant. Economically, this is an indicator of reduced quality of destinations and increased costs of operations, both of which deter competitiveness and discourage repeat visits in the long term. Moreover, the use of renewable energy (RE) is in favor of tourism: $\ln RE = 0.276$ ($p = 0.023$), which means that a 1-percentage point gain in the use of renewable energy is

likely to lead to a 0.28-percentage point gain in tourism, with the effect being moderate and statistically significant. This is economically indicative of reduced volatility of the cost of energy as well as enhanced destination credibility, as renewables reduce the input of fossil fuels over time. Moreover, the impact of technological innovation (TI) on the development of tourism is strongly positive: $\ln TI = 0.301$ ($p = 0.004$); thus, an increase in TI by 1 percent increases TD by about 0.30%. In economic terms, this connection corresponds to efficiency gains and service differentiation, which enhance destination quality and the satisfaction of visitors. Likewise, foreign direct investment (FDI) has the most significant long-run impact: $\ln FDI = 2.162$ ($p = 0.008$), indicating that a 1% increase in FDI is associated with a 2.16% rise in TD; therefore, the elasticity is large and highly significant. This outcome captures FDI's role in transferring technology, capital, and managerial standards that strengthen destination competitiveness.

Table 5. ARDL long-run and short-run estimates.

Long-run equation				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
$\ln ED$	−0.7251 *	0.396	−1.828	0.078
$\ln RE$	0.276 **	0.115	2.404	0.023
$\ln TI$	0.301 ***	0.097	3.107	0.004
$\ln FDI$	2.162 ***	0.756	2.859	0.008
C	7.664	7.639	1.003	0.032
Short-run equation				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
$\Delta \ln ED$	−3.47	3.061	−1.134	0.274
$\Delta \ln RE$	−3.316 *	1.666	−1.99	0.064
$\Delta \ln TI$	0.582 *	0.329	1.77	0.096
$\Delta \ln FDI$	0.227 *	0.118	1.912	0.074
ECT_{t-1}	−0.219 ***	0.046	−4.823	0.000
R^2	0.925			
Adjusted R^2	0.782			
F-statistic	6.491 ***			0.002

Rejection of the unit-root null is coded by (***), (**), and (*), denoting the 1%, 5%, and 10% significance thresholds, respectively.

In contrast, the short-run equation shows weaker and mostly borderline effects, which is typical when adjustment is gradual. The contemporaneous change in environmental degradation (ΔED) is negative but not statistically significant (-3.47 ; $p = 0.274$); therefore, immediate environmental shocks do not measurably impact tourism development (TD) on the initial level. Meanwhile, the change in renewable energy usage (ΔRE) is negative and only weakly significant (-3.316 ; $p = 0.064$), whereas the changes in technological innovation ($\Delta TI = 0.582$; $p = 0.096$) and foreign direct investment ($\Delta FDI = 0.227$; $p = 0.074$) are slight, positive, and borderline at the 10% level. Crucially, the error-correction term is negative and highly significant ($ECT_{t-1} = -0.219$; $p < 0.001$); accordingly, about 21.9% of any disequilibrium is corrected each period, and the implied half-life of a shock is roughly 2.8 periods. Moreover, the negative and highly significant error-correction term provides internal confirmation of cointegration among the variables, which is entirely consistent with the earlier bounds test. In the Autoregressive Distributed Lag (ARDL) framework, such a coefficient indicates that deviations from equilibrium are corrected over time and, importantly, it also implies the presence of long-run Granger causality running from the explanatory variables to tourism development (TD). Thus, short-run fluctuations tend to fade, and the system steadily returns to its long-run path. Moreover, the model fit is strong

($R^2 = 0.925$; adjusted $R^2 = 0.782$), and the joint F-test confirms overall significance ($p = 0.002$). Consequently, the long-run coefficients carry the central message, while the significant correction speed ensures convergence.

Interpreting the contrast between long-run and short-run estimates is instructive. First, environmental degradation (ED) matters in the long run but not in the short run. Conceptually, destination quality, ecosystem services, and health risk perceptions diffuse slowly through markets; therefore, the damage from pollution or habitat loss tends to accumulate and then manifest in reputation, repeat visitation, and product variety. In the short term, however, tourism operators and visitors can temporarily offset localized degradation through pricing, marketing, or substitution across sites and seasons; hence, the immediate effect of ΔED is statistically weak. In this context, international research indicates that pollution can reduce destination appeal over time (Zhang et al., 2020; Su & Lee, 2022). Our results confirm this, as environmental degradation is insignificant in the short term but detrimental to tourism development in the long term.

Second, renewable energy usage (RE) positively impacts tourism development (TD) in the long run, although it exhibits a slight, negative, and only borderline effect in the short run. This asymmetry is plausible. Scaling renewables in the short run could be associated with construction activities, grid enhancement, tariff changes, and knowledge by doing; as a result, the operating expenses and short-term disturbances can affect tourism businesses. Nevertheless, over time, the use of cleaner energy would decrease the amount of pollutants in the air, improve air quality at the destination, and increase the environmental credibility of the destination. Therefore, it enhances tourism brands and minimizes energy volatility in terms of cost for hotels, transportation and attractions. These channels are supported by comparative studies in various countries and have connected renewable energy and green innovation to enhancing the environmental quality and, consequently, to tourism competitiveness reporting lasting gains as the energy transition matures (Khanal et al., 2022; Y. Guo & Chai, 2025).

Third, the long-run gains from technological innovation (TI) and foreign direct investment (FDI) are sizeable and robust, whereas their short-run effects are muted. This pattern is typical of capacity-building variables. Innovation in tourism diffuses through energy efficiency, digital services, smart mobility, and environmental management; thus, its payoff amplifies with adoption and scale, albeit not instantaneously. Over the past few years, the TNTO has advanced the digitalization of the sector by expanding broadband coverage in tourist areas, strengthening the national portal DiscoverTunisia, and simplifying administrative procedures for tourism facilities. It has also promoted start-up initiatives for digital tourism content and explored the introduction of a multi-service electronic card for visitors. These measures align with regional priorities that emphasize digital tools and smart-destination systems as levers of competitiveness and sustainability (Blue Plan/UNEP-MAP, 2022; TNTO, 2024).

Similarly, FDI often finances quality upgrades, new products, and international linkages that take time to complete and to market; therefore, the short-term effect can be small while the long-run elasticity is large. Cross-country analyses consistently document that FDI supports tourism growth over longer horizons, especially when paired with stable institutions and infrastructure (Antwi, 2022).

Combined, the evidence suggests a logical agenda to policy and practice. In the long run, reducing environmental degradation (ED), promoting renewable energy (RE), and technological innovation (TI) will enhance tourism development (TD). Meanwhile, foreign direct investment (FDI) has the potential to enhance such gains through capital deepening and knowledge transfer. In the short run, the adjustment costs may manifest themselves, especially in the process of energy transitions; however, as the error-correction speed is very

large, the costs are temporary and the sector will return to long-run equilibrium. As a result, managers and policymakers should focus on the long-term management of pollution, the predictable use of renewable energy, and environments that encourage innovation through investment, the mitigation of rollout tensions, such as staging construction, stabilizing tariffs, and providing specific assistance to small- and medium-sized tourism enterprises. The experiences of various countries point to the same conclusion: destinations that contribute to improving environmental quality and energy systems have the opportunity to secure demand and increase resilience in the long run.

The results for Tunisia resonate with regional and international evidence, though notable distinctions emerge. The negative long-run effect of environmental degradation on tourism development agrees with findings for Egypt and Morocco, where pollution and coastal stress deter international arrivals (Ren et al., 2019; Kwakwa, 2024). Likewise, the positive roles of renewable energy and technological innovation correspond to evidence from some MENA countries, which shows that clean energy adoption and eco-innovation enhance destination competitiveness and environmental resilience (Abdullayev et al., 2023; Amer et al., 2024). Nevertheless, the elasticities estimated for Tunisia are somewhat larger. This likely reflects its smaller market size, accelerated energy transition momentum, and the sector's heightened sensitivity to improvements in environmental and technological conditions. In contrast, the strong effect of FDI exceeds that reported for broader North African nations (Adeola et al., 2020; Soumaré, 2015), suggesting that institutional stability and proximity to European markets attract higher-quality, tourism-oriented investment. These comparative nuances underscore Tunisia's distinctive position in the region and clarify why structural transition dynamics shape the sustainability of its tourism sector.

After interpreting our empirical findings, we examine the robustness of our ARDL model. Table 6 reports the outcomes of the conducted tests, with diagnostic checks covering heteroskedasticity, serial correlation, and residual normality. In the same regard, Figure 2 examines the stability properties of the estimated coefficients over time.

Table 6. Diagnostic tests.

Diagnostic	Test	Coefficient	Prob.	Decision
Serial Correlation	Breusch–Godfrey LM	0.276	0.762	Absence of serial correlation
Heteroskedasticity	Breusch–Pagan–Godfrey	1.023	0.459	Homoskedasticity.
Normality	Jarque–Bera	0.658	0.719	Residuals are normally distributed.

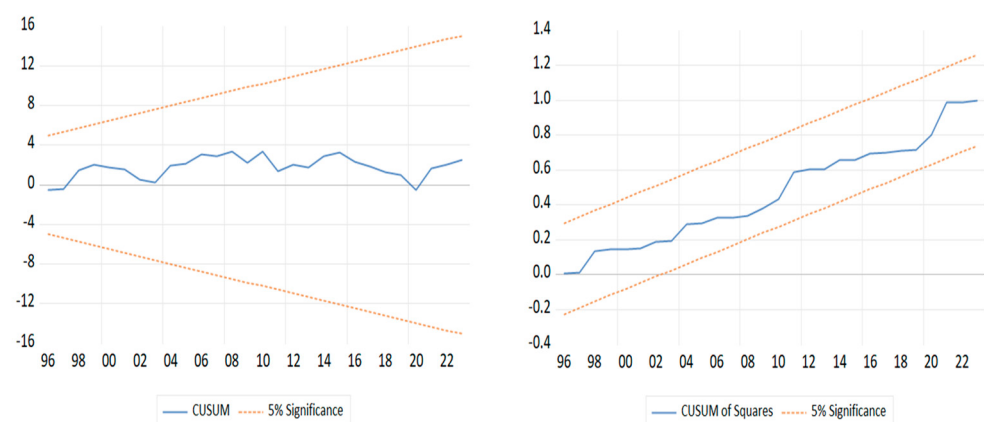


Figure 2. CUSUM and CUSUM squared plots.

The diagnostic results in Table 6 provide strong support for the adequacy of the ARDL specification. The Breusch–Godfrey LM statistic ($p = 0.762$) confirms the absence of serial

correlation, which suggests that the chosen lag structure is appropriate and that dynamic effects are well captured. Likewise, the Breusch–Pagan–Godfrey test ($p = 0.459$) indicates no heteroskedasticity, meaning that the variance of the residuals is stable and the estimated standard errors remain valid. In addition, the Jarque–Bera statistic ($p = 0.719$) shows that the residual series exhibits normality, which enhances the reliability of inference in a small-sample setting. Both CUSUM and CUSUM of Squares in Figure 2. stay within the 5% significance bands; therefore, we do not reject parameter constancy. Hence, no structural break is detected in either the mean dynamics or the error variance. Consequently, the Autoregressive Distributed Lag (ARDL) model is stable, and inference is reliable. Moreover, this stability supports the credibility of the long-run elasticities and the short-run adjustment captured by the error correction term and, thus, strengthens the interpretation of equilibrium relationships and convergence speed. Thus, our estimated model provides a consistent framework for evaluating the role of environmental degradation, renewable energy usage, technological innovation, and foreign direct investment in shaping the development tourism in Tunisia.

To reinforce the long-run evidence from the ARDL model, we re-estimate the cointegrating relation by applying Fully Modified Ordinary Least Squares (FMOLS). FMOLS is designed to address endogeneity and serial correlation, thereby reducing small-sample bias and yielding efficient long-run coefficients.

As shown in Table 7, the estimates provided by FMOLS and the ARDL approach convey the same long-run narrative. Environmental degradation (ED) is negative and marginal in both models (ARDL: -0.725 ; FMOLS: -0.633). Renewable energy (RE) has a positive and significant impact of 5% in both cases, with near-identical elasticities (0.276 and 0.298). Likewise, technological innovation (TI) is positive and highly significant in both; moreover, the FMOLS elasticity (0.427) modestly exceeds the ARDL value (0.301) yet remains within an overlapping range. Foreign direct investment (FDI) is strongly positive in both models (ARDL: 2.162; FMOLS: 2.766) and significant, albeit with wider uncertainty under FMOLS; the ranking of effects is preserved. Consequently, signs are identical and magnitudes are close across all regressors; accordingly, the FMOLS re-estimation corroborates the ARDL long-run coefficients and, thus, confirms the robustness of our elasticities. Consequently, the concordance across estimators confirms the robustness of our long-run elasticities for Tunisia's tourism development.

Table 7. FMOLS long-run coefficient estimates.

Fully Modified Least Squares (FMOLS)				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
<i>lnED</i>	-0.633^*	0.325	-1.948	0.061
<i>lnRE</i>	0.298^{**}	0.131	2.273	0.031
<i>lnTI</i>	0.427^{***}	0.134	3.183	0.003
<i>lnFDI</i>	2.766^{**}	1.290	2.144	0.041
C	4.973	6.501	0.765	0.451

Rejection of the unit-root null is coded by (***), (**), and (*), denoting the 1%, 5%, and 10% significance thresholds, respectively.

The convergent ARDL and FMOLS results have clear policy value for Tunisia. Tourism development rises with green energy, technological innovation, and foreign direct investment, yet it falls with environmental degradation; therefore, growth in a sector crucial for jobs and foreign currency must be green. Accordingly, it is necessary to tighten pollution control and enforcement, and pair this with time-bound support for firm-level efficiency, rooftop solar, and storage. Moreover, we suggest phasing grid upgrades and keeping tariffs predictable to ease short-run frictions from the energy transition. Likewise, promoting

innovation through targeted R&D credits, digitalization programs, and credible green certification is recommended. In parallel, it is necessary to attract foreign direct investment that meets environmental standards and prioritizes clean energy, circular practices, and higher-value products. Finally, we recommend investing in coastal protection, heritage up-keep, and urban cleanliness and publishing joint energy–environment–tourism indicators; as a result, reputation will improve, risks fall, and the long-run gains identified by both estimators can be realized.

To complement the cointegration evidence and clarify directional linkages, we implemented pairwise Granger causality tests among tourism development (TD) and its determinants—environmental degradation (ED), renewable energy (RE), technological innovation (TI), and foreign direct investment (FDI). In this setting, the variable X is said to Granger-cause the variable Y if the past of variable X improves the prediction of variable Y beyond the information in variable Y 's own past (Granger, 1969; Engle & Granger, 1987). These tests provide a stationary representation with standard lag-length selection and a dynamic check on the direction of influence, which is consistent with the ARDL-ECM framework. Because cointegration implies at least one-way causality, these results identify whether the long-run associations documented above are accompanied by short-run predictive causality, thereby informing policy sequencing model robustness.

The link between the variables reveals the presence of Granger causality, as determined by the F-statistic. Table 8 reports the pairwise Granger-causality outcomes and the corresponding direction of influence, where unidirectional causality from the left variable to the right is denoted by ($\rightarrow$), the reverse by ($\leftarrow$), bidirectional causality by ($\leftrightarrow$) when both variables cause each other, and no detected causality by ($\neq$). The results corroborate the RADL-ECM evidence. Specifically, environmental degradation Granger-causes tourism development ($ED \rightarrow TD$), while the reverse direction is not supported. This finding implies that changes in environmental conditions precede and help to explain subsequent movements in tourism activity. Combined with the long-run negative elasticity, this confirms that environmental deterioration tends to lead, and ultimately contribute, to declines in tourism performance rather than merely coincide with them. Likewise, renewable energy and technological innovation both Granger-cause tourism development ($RE \rightarrow TD$; $TI \rightarrow TD$), whereas feedback from tourism to these factors remains weak or insignificant.

Table 8. Pairwise Granger causality test.

Null Hypothesis	F-Statistic	Decision	Causality Direction
$\ln ED$ deos not Granger cuase $\ln TD$	4.1215 **	Reject	$\ln ED \rightarrow \ln TD$
$\ln TD$ deos not Granger cuase $\ln ED$	1.2661	Accept	
$\ln RE$ deos not Granger cuase $\ln TD$	4.2485 **	Reject	$\ln RE \rightarrow \ln TD$
$\ln TD$ deos not Granger cuase $\ln RE$	1.6073	Accept	
$\ln TI$ deos not Granger cuase $\ln TD$	3.6311 **	Reject	$\ln TI \rightarrow \ln TD$
$\ln TD$ deos not Granger cuase $\ln TI$	2.1666	Accept	
$\ln FDI$ deos not Granger cuase $\ln TD$	5.8957 ***	Reject	$\ln FDI \leftrightarrow \ln TD$
$\ln TD$ deos not Granger cuase $\ln FDI$	2.7455 *	Reject	
$\ln ED$ deos not Granger cuase $\ln RE$	2.6321 *	Reject	$\ln ED \rightarrow \ln RE$
$\ln RE$ deos not Granger cuase $\ln ED$	1.6547	Accept	
$\ln ED$ deos not Granger cuase $\ln TI$	3.1441 **	Reject	$\ln ED \rightarrow \ln TI$
$\ln TI$ deos not Granger cuase $\ln ED$	1.5874	Accept	

Table 8. Cont.

Null Hypothesis	F-Statistic	Decision	Causality Direction
$\ln ED$ deos not Granger cuase $\ln FDI$	0.2822	Accept	$\ln ED \neq \ln FDI$
$\ln FDI$ deos not Granger cuase $\ln ED$	0.7616	Accept	
$\ln RE$ deos not Granger cuase $\ln TI$	3.1463 *	Reject	$\ln RE \leftrightarrow \ln TI$
$\ln TI$ deos not Granger cuase $\ln RE$	4.6874 **	Reject	
$\ln RE$ deos not Granger cuase $\ln FDI$	1.3541	Accept	$\ln FDI \rightarrow \ln RE$
$\ln FDI$ deos not Granger cuase $\ln RE$	4.7587 **	Reject	
$\ln TI$ deos not Granger cuase $\ln FDI$	2.1161	Accept	$\ln FDI \rightarrow \ln TI$
$\ln FDI$ deos not Granger cuase $\ln TI$	4.8557 **	Reject	

(***), (**), and (*), denoting the 1%, 5%, and 10% significance thresholds, respectively.

Conversely, foreign direct investment and tourism development exhibit bidirectional causality ($FDI \leftrightarrow TD$), suggesting a feedback loop in which external capital fosters expansion and quality improvements, and stronger tourism activity, in turn, attracts further inflows. These findings align closely with the long-run elasticities, reinforcing the interpretation that Tunisia's tourism dynamics are primarily driven by environmental and technological conditions, with FDI acting as a mutually reinforcing channel.

5. Conclusions

This study examined the long- and short-run relationships between environmental degradation (ED), renewable energy use (RE), technological innovation (TI), and foreign direct investment (FDI) and their linkages with tourism development (TD) in Tunisia. In this country, tourism plays a crucial role in driving economic growth and generating foreign currency earnings. Using annual time-series data from 1990 to 2023 and adopting an Autoregressive Distributed Lag (ARDL) approach, complemented by a Fully Modified Ordinary Least Squares (FMOLS) robustness check, the analysis captured both equilibrium relationships and adjustment dynamics within a single, coherent framework. By integrating environmental, energy, innovation, and investment dimensions, this study seeks to clarify how structural factors jointly shape the trajectory of tourism in a developing economy undergoing economic and environmental transitions.

The empirical evidence highlights that environmental degradation is negatively related to tourism development in the long run, consistent with the notion that environmental quality is a crucial determinant of destination attractiveness. Conversely, renewable energy consumption, technological innovation, and foreign direct investment all exhibit positive and statistically significant long-run connections with tourism development, underscoring the importance of clean energy adoption, innovation-driven competitiveness, and external capital inflows in sustaining the sector. Short-run dynamics appear weaker and sometimes counterintuitive; however, the significant and negative error-correction term suggests a stable adjustment process toward long-run equilibrium. Diagnostic tests and stability checks reinforce the robustness of these results. At the same time, the FMOLS estimates broadly corroborate the ARDL findings, thereby strengthening confidence in the reliability of the long-run elasticities.

Theoretically, these results contribute to the literature on the tourism–environment–growth nexus by showing that tourism development co-evolves with environmental, technological, and financial conditions rather than acting solely as a driver of macroeconomic expansion. Methodologically, the adoption of ARDL for small-sample, mixed-order data, supported by FMOLS to address endogeneity and serial correlation, provides a credible framework that may be applied in other emerging contexts. Empirically, this study offers the

first integrated evidence for Tunisia, thereby filling a regional gap and contributing to debates on sustainable tourism pathways in North Africa and comparable developing economies.

Beyond equilibrium estimation, the Granger causality analysis confirms the dynamic direction of influence among the variables. Environmental degradation, renewable energy, and technological innovation Granger-cause tourism development, indicating that environmental quality, cleaner energy use, and innovation precede improvements in sectoral performance. Conversely, tourism development and foreign direct investment exhibit bidirectional causality, revealing a feedback loop in inflows. These causal links reinforce the robustness of the ARDL–FMOLS results and clarify the sequencing of policy priorities for Tunisia’s sustainable tourism transition.

From a policy perspective, the findings provide evidence-based guidance for Tunisia’s sustainability transition. In the short term, the negative elasticity of tourism development with respect to environmental degradation implies that government authorities should tighten environmental regulations, improve waste and water management, and protect natural ecosystems. Local municipalities and community groups should likewise support these efforts through awareness and monitoring, since even modest environmental gains can raise destination quality. In the medium term, the positive elasticities of renewable energy and technological innovation suggest that scaling up clean-energy initiatives and fostering digital and eco-innovation will generate measurable competitiveness gains. Accordingly, policymakers should introduce fiscal incentives for solar-powered and energy-efficient tourism facilities, while private tourism operators should invest in smart-destination tools and resource optimization technologies. Development banks and foreign investors can reinforce this process by mobilizing green financing and supporting local capacity-building. In the long term, the large elasticity of tourism development with respect to foreign direct investment indicates that investment authorities should prioritize green FDI that bundles renewable energy, digital infrastructure, and sustainable transport. Therefore, strategic partnerships with the private sector can translate external capital into the diffusion of innovation, renewable energy adoption, and sustainable infrastructure up-grading. Collectively, these sequential measures would enable Tunisia to anchor its tourism sector within a sustainable development framework and contribute to international commitments, such as the Sustainable Development Goals.

While the presented analysis offers valuable lessons, some constraints remain. Data constraints restricted the analysis to aggregate proxies, which may not fully capture the multidimensional nature of innovation or environmental degradation. The focus on a single country limits external validity, and the reliance on time-series limits our ability to draw definitive causal conclusions. Accordingly, while the results are robust within the Tunisian context, they should be interpreted with caution when generalizing to other settings. Moreover, as the analysis is based on national-level data, it may not fully reflect the regional heterogeneity that characterizes Tunisia’s tourism landscape, where coastal zones such as Sousse, Hammamet, and Djerba Island dominate international arrivals, while interior regions face distinct structural and environmental challenges. Future analyses could use spatial and sectoral data to trace regional heterogeneity, employ panel-data techniques to capture temporal and cross-regional variation, and draw on hotel-level and firm-level datasets to clarify mechanisms using credible causal designs (e.g., natural experiments or nonlinear models).

Comparative studies across North Africa or other emerging economies could also shed light on regional similarities and differences, thereby enhancing the transferability of policies. Moreover, integrating climate-related risks and resilience measures into the analysis would enrich the understanding of how tourism can adapt to evolving environmental challenges.

In conclusion, the evidence indicates that development of tourism in Tunisia is closely linked to environmental quality and may benefit from greater use of renewable energy, technological innovation, and targeted foreign investment. These interconnections provide valuable insights for designing coherent, sustainability-oriented policies that strengthen the tourism sector while preserving ecological and economic balance. By aligning policy with these structural drivers, Tunisia can consolidate its position as a competitive and sustainable destination, offering guidance of broader relevance for other developing countries navigating similar sustainability transitions.

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