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Quantifying Greenhouse Gas Emissions through Financial Market's Development in Tunisia: Empirical Evidence from Novel Dynamic ARDL Techniques

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ABSTRACT

This study investigates the impacts of financial development (FMD), GDP per capita (GDP), primary energy consumption (ENG), and trade openness (TO) on total greenhouse gas emissions (EQ) in Tunisia over the period 2000–2021. Using the ARDL approach, complemented by FMOLS, DOLS, and CCR estimators, the results indicate that financial development significantly reduces emissions, reflecting its role in financing green projects and fostering technological innovation. In contrast, GDP per capita and energy consumption exert a positive and substantial effect on emissions, highlighting the carbon-intensive nature of Tunisian growth. Trade openness has a limited short-term effect but contributes to emission reductions in the long term. The negative and significant error-correction coefficient shows a rapid adjustment towards long-term equilibrium. These findings emphasise that promoting sustainable finance, accelerating the energy transition, and implementing well-regulated trade policies are essential levers for mitigating emissions and enhancing environmental sustainability in Tunisia.

Keywords: Financial Market Development, Technological Innovation, ARDL Approach, Environmental Sustainability, Greenhouse Gas Emissions
JEL Classifications: G1, G2, G15, Q2, Q5

1. INTRODUCTION

In the contemporary landscape of global challenges, the concept of sustainable development has emerged as a vital objective, seeking to harmonize economic growth, social inclusion, and environmental protection (Chouaïbi and Guenichi, 2023; Gava et al., 2025; Gharbi et al., 2025; Zakari et al., 2024; Zakari et al., 2021). However, the escalating levels of greenhouse gas emissions worldwide pose a noteworthy obstacle to achieving environmental sustainability, leading to air pollutants and climate change (Landi et al., 2024; Naseer et al., 2025). Consequently, environmental quality has become a critical concern for governments and decision makers striving to reduce ecological degradation and ensure a livable environment for both people and the planet (Wu et al., 2025). In this context, the international community has not adequately addressed large-scale environmental problems, including climate change and global warming, and there are significant disparities in environmental performance across communities. The Intergovernmental Panel on Climate Change (IPCC) indicates that high risk from climate change is estimated to emerge with a temperature increase of 1.1–3.6◦C above pre-industrial levels (O'Neill et al., 2017). Despite climate change is a global issue, responses to it vary significantly for all communities. More recently, numerous studies have shown that the climate change patterns and other environmental policies are significantly affected by institutional quality including political stability,

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democracy, corruption, and others diverse political institutions (Naseer et al., 2025). The environmental economics literature employs various environmental and ecological indicators to quantify environmental impacts, including ecological footprints (Shah et al., 2023), air and water pollutant emissions (Chishti and Sinha, 2021; Jabeen et al., 2023; Zakari et al., 2024), and particulate matter and energy consumption (Considine et al., 2024). Nevertheless, the aforementioned indicators focus primarily on the environmental dimension while overlooked the economic aspect of sustainability (Landi et al., 2024).

Recently, numerous studies have focused on identifying the determinants of environmental quality across various economic contexts to support informed policy decisions (Naseer et al., 2025). Among these determinants, the role of the financial system has gained growing attention globally, particularly following the adoption of the 2030 Agenda by 193 UN member countries. Financial development influences production and consumption patterns, thereby shaping the environmental footprint of economies (Fallah Shayan et al., 2022). A well-functioning financial system enhances access to capital for individuals, businesses, and governments, potentially leading to increased economic activity and environmental stress (Fallah Shayan et al., 2022). Conversely, it can also encourage investments in green technologies and ecological projects (Chishti and Sinha, 2021). Within the financial system, financial stock markets play a critical role in mobilizing and allocating resources from savers to borrowers (Aggarwal and Goodell, 2009). These financial markets, through mechanisms such as equity and debt financing, can affect environmental outcomes via three primary channels: sustainability, production, and consumption (Chen et al., 2025). The sustainability channel posits that financial stock market development supports environmentally responsible investments by promoting investment in renewable energy and reducing carbon emissions (Kwilinski et al., 2025). The production channel suggests that improved access to financial instruments can stimulate industrial activity, thereby intensifying resource use and emissions (Yiadom et al., 2025). Lastly, the consumption channel highlights how financial market development increases consumer access to credit, growing demand and energy consumption, which may further degrade environmental quality (Charfeddine & Ben Khediri, 2016; Kwilinski et al., 2025).

While financial markets are progressively important, their impact on environmental development remains underexplored in the Tunisian context. Several emerging countries, such as Tunisia, are striving to reconcile economic growth and environmental sustainability. The country's financial market has experienced notable reforms aimed at improving efficiency, access, and stability. However, the environmental implications of these developments have not been systematically explored. This study seeks to fill this gap literature by investigating the association between financial market development and environmental quality in Tunisia. Notably, the financial markets play crucial roles in mobilizing capital, allocating resources, and supporting economic development. Theoretically, the development of financial markets can promote environmental sustainability by facilitating investments in green technologies, renewable energy, and environmentally responsible enterprises. It can also enhance transparency and accountability through environmental, social, and governance (ESG) scores. Conversely, financial market development may also lead to increased industrial activity, higher energy consumption, and greater environmental degradation if not aligned with sustainable practices. Emerging economies such as Tunisia are currently undergoing financial reforms aimed at developing and modernizing their financial markets. These reforms are expected to improve access to capital, stimulate private sector growth, and attract foreign investment. However, the environmental implications of these developments remain largely unexplored. Given Tunisia's mounting environmental challenges, understanding the environmental impact of financial market development has become essential for informed policymaking.

All in all, our study contributes to the existing environmental economics literature in several ways. First, it addresses a notable gap by exploring the impact of financial market development on environmental quality in Tunisia. Unlike prior studies that often conflate financial institutions with financial markets, this research focuses exclusively on market-based financial development. It examines how different dimensions of financial markets including access, depth, efficiency, and stability, affect environmental indicators. This study aims to provide nuanced insights into the twofold role of financial markets as both enablers of sustainable development and potential contributors to environmental tensions and degradations (De Haas and Popov, 2019). Notably, the paper contributes to the growing body of literature on sustainable finance and offers practical insights for aligning Tunisia's financial market development with its environmental goals. Second, to the best of the authors' knowledge, no comprehensive study that examines the long-run dynamics of the complex interaction between financial markets and environmental quality in the Tunisian context. Third, in accordance with our research objective, this study employs the Autoregressive Distributed Lag (ARDL) model, complemented by Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) estimators. These tools are particularly suitable for analyzing dynamic relationships in small sample contexts. The use of dynamic ARDL has become increasingly popular in environmental economics (Ben Salem et al., 2022; Gava et al., 2025). For instance, Chaouali et al. (2023) employed both linear and nonlinear ARDL models to investigate the nexus between renewable energy, service sector growth, and CO_2 emissions in Tunisian area. Their outcomes revealed that while renewable energy and service growth positively affect emissions in the long run, nonlinear shocks (such as energy crises) can enhance environmental quality. This methodological advancement allows for capturing asymmetric relationships and short-run dynamics that traditional models may overlook. Fourth, By focusing on Tunisia, this research adds to the growing body of literature on sustainable finance and offers valuable insights for policymakers seeking to align green financial development with environmental objectives.

Our results indicate that financial development significantly reduces emissions, reflecting its role in financing eco-friendly projects and boosting technological innovation. However, we observe that the GDP per capita and energy consumption have a positive and substantial effect on emissions, highlighting the carbon-intensive nature of Tunisian growth. Besides, we observe that the trade openness has a limited short-term effect but contributes to emission reductions in the long term. The negative and significant error-correction coefficient indicates a rapid adjustment towards long-term equilibrium. This study offers valuable policy insights for mitigating environmental degradation through the adoption of energy-efficient technologies. Furthermore, financial development can significantly contribute to enhancing environmental quality.

The remainder of this manuscript is systematized as follows:" A brief literature review" section 2 deals with the literature review. "Econometric Method and Data" section 3 designates the used data and summaries the econometric model specification; and "Results and Discussions" section 4 reports and discusses the empirical findings; and "conclusions and policy implications" section 5 concludes the article and offers some policy implications.

2. LITERATURE REVIEW

The nexus between financial market development and environmental degradation has increasingly attracted the attention of both academics and practitioners over the past two decades(Subhani et al., 2025; Wijethunga et al., 2024). According to Levine (1999), financial development refers to the process through which markets, financial tools, and intermediaries improve their capacity for information processing, contract enforcement, and the execution of various financial transactions. This helps the financial system carry out its functions more efficiently. The literature presents a complex and often contradictory picture, with studies highlighting both positive and negative environmental outcomes associated with financial sector's development (FSD). Theoretically, financial markets can influence environmental quality through multiple channels (Bui, 2020). The sustainability channel suggests that well-developed financial markets facilitate investments in green technologies, innovation technology, and sustainable industries by improving access to capital (Bui, 2020; Subhani et al., 2025). This can lead to reduced emissions and enhanced environmental performance. However, some channels of production and consumption suggest that financial development may exacerbate environmental degradation by stimulating industrial growth and consumer demand, thereby boosting resource use and pollution (Zhang et al., 2024).

Research scholars have largely produced mixed results. For example, Charfeddine and Ben Khediri (2016) found that financial development in the UAE contributes to environmental degradation due to increased energy consumption. Similarly, Shah et al. (2023) reported that financial development leads to higher CO_2 emissions in emerging economies. In the same vein, Mukhtarov et al. (2024) assessed the nexus between financial development and carbon emissions in Kazakhstan from 1993 to 2020. Their results indicate that financial development increases environmental degradation through CO_2 emissions in Kazakhstan. Specifically, their results show that a 0.17% upsurge in carbon emissions is linked to a 1% upsurge in financial development. However, Mavlutova et al. (2025) emphasized the role of financial markets in promoting environmental sustainability through green investments and technological innovation. Using ARDL technique, Cosmas et al. (2019) explored the nexus between financial development and carbon emissions over the period 1981 to 2016. Their finding indicated a neutral effect, suggesting that financial development neither significantly augmented nor decreased carbon emissions. By employing a vector error correction model and Granger causality tests, Shahbaz et al. (2013) investigated the impact of GDP, energy consumption, foreign direct investment, financial development, and trade openness on environmental pollution in Malaysia for the period 1971–2011. The results demonstrate that all five factors including GDP, energy consumption, foreign direct investment, financial development, and trade openness have positive and significant effects on CO_2 emissions. By applying the generalized method of moments (GMM), Alam et al. (2015) investigated the impact of population density, energy resources, energy consumption, and financial development on environmental pollution, measured by CO_2 emissions, in Malaysia between 1975 and 2013. Their findings indicate that both energy consumption and financial development significantly contribute to higher CO_2 emissions. Using ARDL model, Wijethunga et al. (2024) demonstrated that the market-based financial development have a positive effect on Australia's environmental quality through the decrease of greenhouse gas emissions in the long run.

Several more recent studies have also examined the crucial role of financial market efficiency and depth (Aman et al., 2024; Qaysi, 2025; Topçu and Dinç, 2024). Topçu and Dinç (2024) argued that efficient financial markets can reduce environmental harm by enabling better allocation of resources and supporting environmentally responsible firms. Prempeh et al. (2024) highlighted the spillover effects of green knowledge and technology facilitated by financial market integration. Other studies, however, show that financial development exsert a positive effect on environmental pollution by allowing consumers to buy expensive goods such as houses and cars at lower costs through credit (Dan, 2024), thereby growing energy consumption and carbon emissions (Chouaïbi and Guenichi, 2023). Ju et al. (2023) investigate the relationship between financial development, foreign direct investment (FDI), technological innovation, good governance and environmental degradation in Arab countries from 1991 to 2019. Their findings revealed that financial development adversely affects sustainability by growing CO_2 emissions, whereas FDI and technological development help reduce ecological degradation.

Few studies have investigated the relationship between green finance and environmental quality in Tunisian context. For instance, Abdouli and Hammami (2015) examined the impact of financial development on environmental quality in MENA countries, including Tunisia, and found a positive correlation between financial development and CO_2 emissions. However, their study did not isolate the effects of financial markets from financial institutions, leaving a gap in understanding the specific role of market-based financial development. Using the generalized method of moments (GMM), Omri and Sassi-Tmar (2013) analyzed the impact of foreign direct investment inflows on economic growth for three African economies (Tunisia, Morocco, and Egypt) over the period 1985–2011. Their empirical results showed that the human capital variable is positively and significantly related to economic growth in Morocco but insignificantly related in Egypt and Tunisia.

Kahouli (2017) found that financial development contributes to economic growth in Tunisia, however, it also increases environmental pressure due to higher energy consumption. This result emphasizes the need for a more nuanced analysis that considers the multidimensional nature of financial markets. Using ARDL approach, Gharbi et al. (2025) investigated the effects of financial development, renewable energy, tourism, and industrialization on carbon emissions in Tunisia from 1988 to 2021. Their empirical results showed that financial development and renewable energy substantially decrease CO_2 emissions, whereas tourism and industrialization contribute to environmental degradation. Similarly, using ARDL approach, Chouaïbi and Guenichi (2023) examined the long-run relationship between economic growth, energy consumption, and financial development in Tunisia. Their results indicate a positive relationship between GDP and CO_2 emissions, suggesting that Tunisia has not yet reached the income threshold required for the Environmental Kuznets Curve (EKC) to take effect.

In Tunisia, financial development has related with increased emissions, emphasizing the need for green finance reforms and well-defined regulations frameworks. The evolving perspectives in the literature on these relationships underscore the importance of revisiting them in the Tunisia context. Specifically, the country's ongoing environmental challenges present a compelling case for further study. Tunisia's environmental challenges have become a significant national problem, making them a mainly intriguing issue for investigation. A profounder understanding of this multifaceted connection will also allow future researches to examine how environmental effects are influenced by various conditions such as renewable energy (Gharbi et al., 2025), green trade openness (Almulhim et al., 2025; Gava et al., 2025), institutional quality (Almulhim et al., 2025), regulatory frameworks, financial development (Wijethunga et al., 2024), socio-economics factors (Erdogan et al., 2025), green technological innovation (Chen et al., 2025), and geopolitical risk (Erdogan et al., 2025). The present study explores Tunisia's environmental quality, concentrating on energy consumption, production, and infrastructure while reviewing the effects of financial development and carbon emissions.

3. ECONOMETRIC METHOD AND DATA

The third section documents the selection of appropriate variables, model specification, data description, and econometric strategy applied to achieve the main objective of our study. To empirically quantify the impact of financial Market's development on greenhouse gas emissions in Tunisia, we adopt the general model expressed in equation (1), where EQ_t denotes environmental quality, FMD_t captures financial market development, and CV_t represents the control variables. This outline allows the assessment of financial development while accounting for economic and structural factors that may influence environmental quality, thus ensuring robust and consistent estimation.

$$EQ_t = f(FMD_t, CV_t) \quad (1)$$

Financial market development enhances their depth, accessibility, efficiency, and stability, facilitating savings mobilisation, optimal resource allocation, and risk management (Cihák et al., 2012; Wijethunga et al., 2023). A mature financial system increases economic productivity while reducing transaction costs (Fama, 1970; Levine, 1999). Nevertheless, its environmental impact remains ambivalent: it supports the financing of clean technologies and green innovation but may also stimulate energy consumption and polluting activities (Tamazian et al., 2009; Sadorsky, 2010; Acheampong et al., 2020), underscoring the need for a precise assessment of its net effects, particularly in the Tunisian context.

This study incorporates three control variables: economic growth, energy consumption, and trade openness. The growth–environment relationship is examined within the framework of the Environmental Kuznets Curve (EKC, Grossman and Krueger, 1991). In Tunisia, economic growth is consistently associated with increased CO_2 emissions, suggesting that the EKC turning point has not yet been reached (Saadaoui and Chtourou, 2022; Gharbi et al., 2025), due to an industrial structure heavily dependent on fossil fuels and polluting industries (Ben Jebli and Ben Youssef, 2017). Energy consumption exhibits a dual effect: the heavy reliance on fossil fuels (≈85 % of the national energy mix) exacerbates environmental degradation (ANME, 2023), whereas the ongoing energy transition may have positive impacts (Ben Youssef et al., 2022). Trade openness affects environmental quality both directly, by reallocating resources between more or less polluting sectors, and indirectly, by stimulating per capita income and the demand for stricter environmental standards (Chebbi et al., 2011). Furthermore, the composition effect, along with commitments under the Paris Agreement and the EU–Tunisia Green Partnership, gradually encourages specialisation in less polluting sectors (GIZ, 2023).

On this basis, the general model of equation (1) is reformulated as equation (2), incorporating GDP per capita, primary energy consumption, and trade openness to more precisely assess their effects on environmental quality.

$$EQ_t = \alpha + \beta_1 FMD_t + \beta_2 GDP_t + \beta_3 ENG_t + \beta_4 TO_t + \varepsilon_t \quad (2)$$

In this equation, FMD_t denotes financial market development, while GDP_t, ENG_t, and TO_t represent GDP per capita in constant local units, primary energy consumption, and trade openness, respectively. β_1, β_2, β_3 and β_4 are the coefficients of the explanatory variables, and ε_t is the model's error term, with t indicating time. To account for the exponential variances in the dataset, a logarithmic transformation is applied, yielding the reformulated model presented as Equation (3).

$$LogEQt = \alpha + \beta_1 LogFMD_t + \beta_2 LogGDP_t + \beta_3 LogENG_t + \beta_4 LogTO_t + \varepsilon_t \quad (3)$$

3.1. Econometric Approach

The current study empirically estimates the model in Equation (3) using the Autoregressive Distributed Lag (ARDL) bounds testing approach to cointegration (Pesaran et al., 2001; Xuan, 2024). The ARDL model is appropriate for small samples and can be referred regardless of whether the variables are in mixed orders of integration (I (0) and I (1)). We used the Augmented Dickey–

Fuller (ADF, 1979) and Zivot–Andrews (Zivot et al., 2002) tests to verify the stationarity of the variables, with the latter allowing for potential structural breaks in times series. The panel ARDL model (Equation 4) was estimated using the optimal lag order lengths, which was selected based on the Akaike Information Criterion (AIC). This method classifies both short- and long-run dynamics and tests for cointegration through the bounds test, yielding robust and interpretable results for Tunisia's macroeconomic data.

$$\begin{aligned} LogEQ_t &= \beta_0 + \beta_1 Log EQ_t + \beta_2 Log FMD_t + \beta_3 LogGDP_t \\ &+ \beta_4 LogENG_t + \beta_4 LogTO_t + \sum_{i=1}^{P} \delta_{1i} LogEQ_i \\ &+ \sum_{i=1}^{P} \delta_{2i} LogFMD_i + \sum_{i=1}^{P} \delta_{3i} LogGDP_i + \sum_{i=1}^{P} \delta_{4i} LogENG_i \\ &+ \sum_{i=1}^{P} \delta_{5i} LogTO_i + \varepsilon_t \end{aligned} \quad (4)$$

The existence of a cointegration relationship among the regressors was tested using the bounds testing approach. Establishing such a relationship is a necessary condition for estimating the long-run coefficients. Specifically, the null hypothesis H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$ is tested against the alternative hypothesis H_1: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$. Once cointegration is confirmed, the Error Correction Model (ECM) is estimated to assess the speed of adjustment of the system towards long-run equilibrium. This model is presented in Equation (5).

$$\begin{aligned} LogEQ_t &= \delta_0 + \sum_{i=1}^{P} \delta_1 LogEQ_{t-i} + \sum_{i=1}^{P} \delta_2 LogFMD_{t-i} \\ &+ \sum_{i=1}^{P} \delta_{3i} LogGDP_{t-i} + \sum_{i=1}^{P} \delta_{4i} LogENG_{t-i} \\ &+ \sum_{i=1}^{P} \delta_{5i} LogTO_{t-i} + \Psi ECT_{t-1} + \varepsilon_t \end{aligned} \quad (5)$$

The presence of cointegration between environmental quality and its explanatory factors suggests the possibility of at least a unidirectional causal relationship among these variables. Therefore, we conducted a Granger causality test, as originally proposed by Granger (1969), to examine causal linkages that are not captured by the ARDL bounds testing approach. Equations (6) and (7) specify the causality models and test the null hypotheses that Y does not Granger-cause X and that X does not Granger-cause Y, respectively.

$$Y_t = \varepsilon_0 + Q_1 Y_{t-1} + \ldots + Q_k Y_{t-k} + \varepsilon_1 X_{t-1} + \ldots \varepsilon_k X_{t-k} + \omega_t \quad (6)$$

$$X_t = \varphi_0 + \vartheta_1 X_{t-k} + \ldots + \vartheta_k X_{t-k} + \varphi_1 Y_{t-1} + \ldots \varphi_k Y_{t-k} + \theta_t \quad (7)$$

Finally, several diagnostic tests were employed to assess the validity and reliability of the Autoregressive Distributed Lag (ARDL) model applied to the analysis of the impact of market-based financial development on environmental quality in Australia. The stability of the estimated parameters was examined using the Ramsey RESET test, as well as the Cumulative Sum of Recursive Residuals (CUSUM) and CUSUM of Squares stability tests. In addition, the Breusch–Godfrey LM test was conducted to detect potential autocorrelation in the residuals, while the Breusch–Pagan–Godfrey and ARCH tests were applied to verify the presence of heteroskedasticity. Furthermore, we employ the Jarque–Bera test to confirm the normality of the error distribution.

To further assess the robustness of our results, Equation (3) was re-estimated using three different methods commonly applied in the empirical literature. These methods include the fully Modified OLS (FMOLS) developed by Phillips and Hansen (1990), Dynamic OLS (DOLS) introduced by Stock and Watson (1993), and Canonical Cointegrating Regression (CCR) proposed by Park (1992). Several recent empirical studies (Apergis and Apergis, 2016; Atsu and Atsu, 2021; Nguyen et al., 2020; Samargandi, 2019) have extensively employed these methods to facilitate a comparative analysis of the results and confirm the robustness of the estimations obtained through the ARDL approach.

3.2. Data

The empirical analysis based on annual data covering the period from 2000–2021. The choice of annual frequency is justified by the fact that most of the relevant statistical information is reported in this format. The data selected with their respective sources are presented in Table 1.

This study fills a gap in the literature by employing five proxy variables to provide a comprehensive measure of market-based financial development. These indicators cover access, depth, efficiency, and stability of financial markets, taking into account the debt, equity, and insurance markets. Specifically, stock market stability is measured by stock price volatility, while insurance market development is proxied by the insurance penetration rate (gross premiums as a percentage of GDP), following Appiah-Otoo and Acheampong (2021). A composite financial market development index is then constructed from these proxies using Principal Component Analysis (PCA), in line with the methodology of Shahbaz et al. (2016). The corresponding time series are presented in Figures 1 and 2.

According to Figure 1 below, between 2000 and 2021, the indicators of financial development in Tunisia display contrasting trajectories. Access to financial markets remains limited and unstable, while market depth shows a gradual improvement from 2010 onwards.

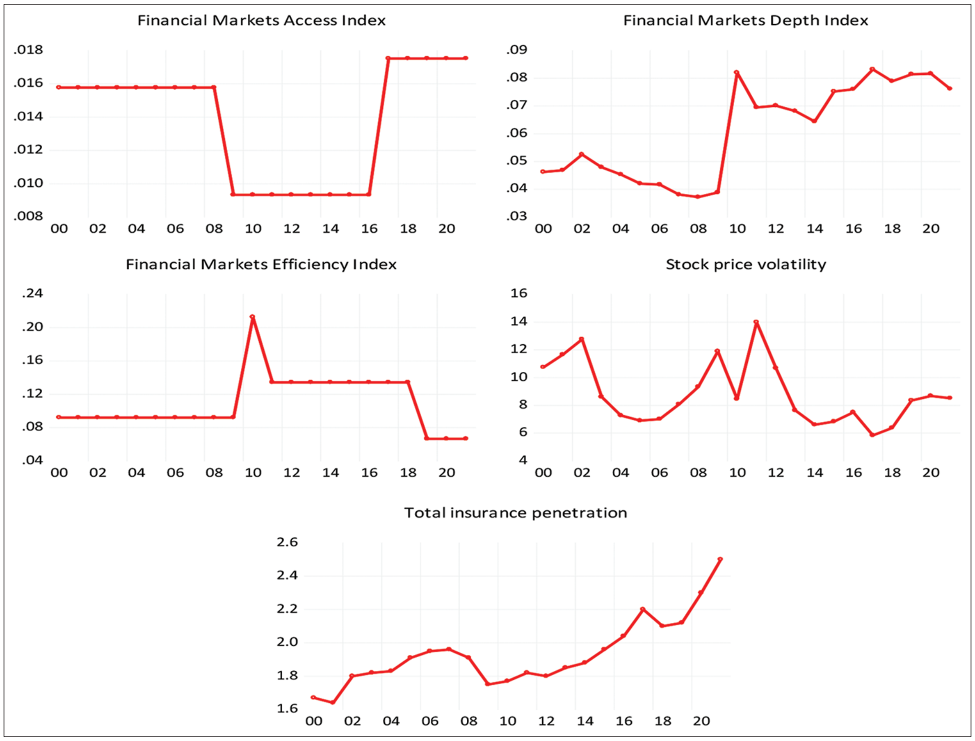
Efficiency, in contrast, fluctuates, exhibiting a brief period of improvement followed by a decline, whereas stock market volatility reflects pronounced instability. By contrast, the insurance penetration rate demonstrates steady growth, reflecting the strength and continued expansion of this sector. Overall, the Tunisian financial system is characterised by structural instability, contrasting with the positive and stabilising dynamics of the insurance market.

According to Figure 2 below, the analysis of economic and environmental variables in Tunisia between 2000 and 2021

Table 1: Proxies of the study variables

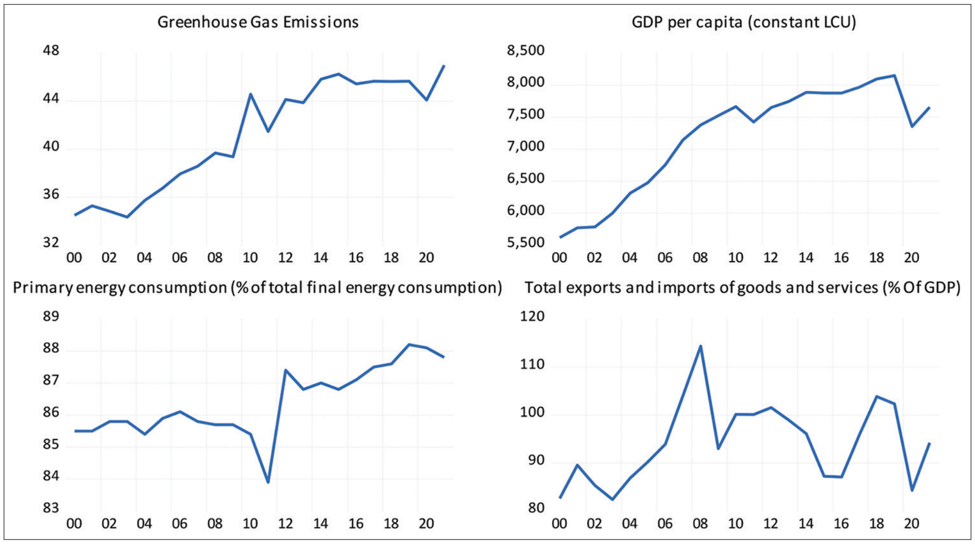
Variables	Measurement	Source of data
EQ	Total greenhouse gas emissions including LULUCF (Mt CO2e). A measure of annual emissions of the six greenhouse gases (GHG) covered by the Kyoto Protocol (carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6)).	World Bank Database
FMD	Financial market access index Financial market depth index Financial market efficiency index	International Monetary Fund
	Stock price volatility Stock	Global Financial Development
	Total insurance penetration (% of GDP)	The Tunisian Federation of Insurance Companies.
GDP	GDP per capita (constant LCU)	World Bank Database
ENG	Primary energy consumption (Percentage of total final energy consumption.	
TO	Total exports and imports of goods and services (% of GDP)	

Figure 1: Time series plots of the proxy variables for the financial market development



Source: Authors' calculations

Figure 2: Time series plots of the dependent variable and other variables used



Source: Authors' calculations

highlights several significant trends. Greenhouse gas emissions show a marked increase, particularly after 2010, reflecting growing environmental pressure linked to economic and energy dynamics. GDP per capita increased steadily until 2014, before stagnating and slightly declining around 2020, likely due to the combined effects of internal shocks and the health crisis.

Primary energy consumption remained relatively stable until 2010, then experienced a decline followed by a gradual recovery, illustrating adjustments imposed by energy constraints. Foreign trade, measured by the exports-to-imports ratio relative to GDP, displayed high volatility, with peaks between 2008 and 2012, followed by persistent fluctuations, revealing Tunisia's vulnerability to international shocks and structural imbalances. Overall, these developments underscore the interdependence between economic growth, energy consumption, and environmental degradation within a context of unstable trade openness.

4. RESULTS AND DISCUSSION

The descriptive statistics presented in Table 2 summarise the main characteristics of the data used, including the mean, median, extremes, standard deviation, skewness, and kurtosis. Most variables exhibit a slight negative skew, indicating a concentration of higher values around the mean, whereas trade openness (Log TO) shows a slight positive skew.

This moderate skewness suggests distributions close to normality, without any pronounced bias. The standard deviations indicate limited dispersion for Log EQ, Log GDP, Log ENG, and Log TO, in contrast to Log FMD, which exhibits greater variability. Overall, these observations confirm the suitability of the series for subsequent econometric analyses. The correlation matrix, summarised in Table 3, shows that all explanatory variables are positively correlated with greenhouse gas emissions. More specifically, economic growth (Log GDP) and energy consumption (Log ENG) exhibit positive and significant correlations with environmental quality (Log EQ), while trade openness (Log TO) displays a moderately positive correlation.

In contrast, market-based financial development (Log FMD) exhibits a very weak and non-significant correlation with Log EQ, suggesting that its direct impact on greenhouse gas emissions remains limited. This indicates that the effect of financial development on environmental quality may be indirect, highlighting the need for a more in-depth econometric analysis. Prior to conducting the time series analysis, it is essential to determine the order of integration for each data series, as shown in Tables 4 and 5. Indeed, testing for stationarity and identifying the order of integration constitute a crucial step before applying econometric methods to time series data. To this end, two complementary unit root tests were employed: the Augmented Dickey-Fuller (ADF) test (1979) and the Zivot-Andrews test (2002), which accounts for the possibility of an endogenous structural break within the series.

The results of the ADF test (Table 4) indicate that some variables (Log EQ, Log FMD, and Log GDP) are non-stationary in levels but become stationary after first differencing, confirming their integration of order one, I(1). In contrast, Log ENG and Log TO are stationary at levels, reflecting an integration of order zero, I(0). Thus, all variables are either I(0) or I(1), which justifies the use of the ARDL methodology, particularly suitable for mixed I(0) and I(1) series.

However, time series may be affected by structural breaks arising from economic, political, or institutional shocks, which can bias

Table 2: Descriptive statistics

Description	Log EQ	Log FMD	Log GDP	Log ENG	Log TO
Mean	3.713	0.684	25.074	4.459	4.543
Median	3.753	0.856	25.126	4.454	4.544
Maximum	3.850	1.704	25.296	4.480	4.739
Minimum	3.536	−1.315	24.728	4.430	4.411
Std. Dev.	0.113	0.802	0.182	0.013	0.087
Skewness	−0.350	−1.107	−0.633	−0.114	0.255
Kurtosis	1.532	3.622	2.031	2.503	2.344
Jarque-Bera	2.425	4.851	2.331	0.274	0.633
Probability	0.297	0.088	0.312	0.872	0.729
Sum	81.680	15.038	551.623	98.096	99.938
Sum Sq. Dev.	0.267	13.518	0.697	0.003	0.160

Source: Authors' calculations

Table 3: Correlation matrix

Variable	Log EQ	Log FMD	Log GDP	Log ENG	Log TO
Log EQ	1.000 -----				
Log FMD	0.031 0.892	1.000 -----			
Log GDP	0.967 0.000	0.088 0.696	1.000 -----		
Log ENG	0.664 0.001	0.609 0.003	0.648 0.001	1.000 -----	
Log TO	0.421 0.051	−0.147 0.513	0.498 0.018	0.061 0.789	1.000 -----

Source: Authors' calculations

Table 4: The results of the unit root test

Variable	Level		1st difference		Order of integration
	t-Statistic	Prob	t-Statistic	Prob	
Log EQ	−1.132	0.681	−8.090	0.000	I (1)
Log FMD	−2.263	0.192	−3.143	0.040	I (1)
Log GDP	−2.354	0.165	−4.123	0.005	I (1)
Log ENG	−3.509	0.064	−6.945	0.000	I (0)
Log TO	−2.889	0.063	−5.127	0.000	I (0)

Source: Authors' calculations

Table 5: Zivot-Andrews test results

Variables	(Level)			(First Difference)		
	DSC	t-stat	P-value	DSC	t-stat	P-value
Log EQ	2017	−2.242	0.099	2016	−4.383	0.051
Log FMD	2009	−6.644	4.500	2012	−4.437	0.034
Log GDP	2010	−2.936	0.043	2004	−6.096	0.306
Log ENG	2012	−4.556	0.004	2012	−9.710	0.001
Log TO	2006	−3.965	0.052	2009	−4.560	0.037
1% critical value:		−5.34			−5.34	
5% critical value:		−4.93			−4.93	
10% critical value:		−4.58			−4.58	

Source: Authors' calculations

the results of standard unit root tests. To address this limitation, the Zivot-Andrews test was applied (Table 5).

This test simultaneously assesses stationarity and the presence of a structural break. The results reveal several significant structural breaks: Log EQ in 2017, Log FMD in 2009, Log GDP in 2010, Log ENG in 2012, and Log TO in 2006. These dates correspond to periods of major economic and institutional transformations in Tunisia, notably the global financial crisis of 2008–2009, the political events of 2011, and the subsequent structural and energy reforms implemented in the following years.

Overall, the tests confirm that the series under study are integrated of mixed order (I(0) and I(1)) and exhibit significant structural breaks. This reinforces the relevance of using the ARDL model, which can accommodate both the heterogeneity of integration orders and the dynamics of short- and long-term adjustments. The optimal ARDL model selected is (1,0,0,1,1), corresponding respectively to Log EQ, Log FMD, Log GDP, Log ENG, and Log TO, and determined using the Akaike Information Criterion (AIC). Finally, the bounds test (Table 6) indicates that the F-statistic (9.921) exceeds the 1% critical value, confirming the existence of a long-term relationship between Log EQ and the explanatory variables.

The analysis of long-term dynamics highlights key structural relationships relevant to Tunisia's environmental policy. The cointegration relationship confirms the existence of a stable equilibrium towards which the variables converge in the long run. The results in Table 7 show that market-based financial development exerts a negative and significant effect, indicating that a sustainable 1% increase in Log FMD leads to a 0.051% reduction in CO_2 emissions. This long-term stabilising effect aligns with the findings of Acheampong et al. (2020) and Wijethunga et al. (2024), suggesting that financial markets, once reaching a certain level of maturity, become institutions capable of sustainably directing savings towards green investments and promoting innovation in clean technologies.

Conversely, GDP per capita exhibits a high and positive long-term elasticity of 0.509 %, highlighting that Tunisia's development model remains structurally and persistently carbon-intensive, consistent with the upward phase of the Environmental Kuznets Curve (Grossman and Krueger, 1991). The most striking result, however, is the long-term elasticity of primary energy consumption, which reaches 3.85 %. This value, markedly higher than those of the other variables, corroborates the IPCC's (2023) assessment as well as Ang's (2007) findings: the composition of the energy mix, heavily dominated by fossil fuels, constitutes the primary structural and persistent determinant of greenhouse gas emissions in Tunisia. The low long-term significance of trade openness indicates, in turn, that this factor has yet to alter the underlying economic structure towards a more or less polluting specialisation (Copeland and Taylor, 2003). Overall, the long-term dynamics depict a trajectory in which financial deepening emerges as the main corrective lever, capable of partially counterbalancing the structural pressures exerted by GDP and primary energy consumption. Short-term results indicate significant immediate adjustments, confirming the existence of a dynamic relationship between greenhouse gas emissions (Log EQ) and the explanatory variables (Table 8). A 1 % increase in financial market activity (D (Log FMD)) leads to an immediate reduction in emissions of –0.039 %, consistent with Daly and Sraïeb (2021) and limited in the short term in emerging economies (Deng et al., 2023). In contrast, a 1 % increase in GDP per capita (D (Log GDP)) raises emissions by +0.372 % (Shahbaz et al., 2017), while energy consumption (D (Log ENG)) has the most pronounced effect (+2.351 %, Ben Cheikh and Ben Zaied, 2021). Foreign trade remains marginal (+0.103 %).

The error correction term (Coint Eq (–1) = –0.901) reveals a high adjustment speed of 90.1 % per period, exceeding that typically reported (Omri, 2013), illustrating the system's responsiveness to cyclical shocks. The modest short-term effect of financial development reflects the time required for green investment deployment (Deng et al., 2023), whereas the predominant impact of energy consumption emphasises the urgency of energy efficiency policies. Overall, market-based financial development contributes to reducing emissions in both the short and long term, whereas economic growth and energy consumption exacerbate them, with a more pronounced cumulative effect over the long term. Foreign trade remains marginal. The model's robustness is confirmed by the R^2 values, which explain 86.6 % of the short-term variation in emissions and 98.1 % in the long term.

Finally, the results of the Granger causality test (Table 9) show that in Tunisia, financial development has no direct effect on GHG emissions, thus reflecting the financial sector's neutrality with regard to the environmental transition. In contrast, a unidirectional causality is observed from GDP per capita and trade openness to GHG emissions, indicating that economic growth and the intensification of external trade increase environmental pressure.

Table 6: The results of the long-run bound test

F-statistic	9.921	Critical values (%)	I (0)	I (1)
		10	2.2	3.09
K	4	5	2.56	3.49
1		2.5	2.88	3.87
		3.29	4.37	

Source: Authors' calculations

Table 7: The long-run coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Log FMD	−0.051	0.014	−3.655	0.003
Log GDP	0.509	0.076	6.724	0.000
Log ENG	3.852	1.382	2.787	0.015
Log TO	−0.178	0.094	−1.891	0.081
C	−7.641	1.871	−4.084	0.001

R-squared: 0.980, Adjusted R-squared: 0.970, F-statistic: 95.358 (0.000). *,** and ***denote significance at the 1%, 5%, and 10% levels, respectively. Source: Authors' calculations

Table 8: The short-run coefficients

Variable	Coefficient	Std. Error	t-statistic	Prob.
D (Log FMD)	−0.039*	0.009	−4.422	0.001
D (Log GDP)	0.372*	0.110	3.382	0.006
D (LOGENG)	2.351*	0.409	5.747	0.000
D (Log TO)	0.103***	0.053	1.945	0.078
Coint Eq(-1)*	−0.901*	0.143	−6.318	0.000

R-squared: 0.865, Adjusted R-squared: 0.832. *,** and ***Denote significance at the 1%, 5%, and 10% levels, respectively. Source: Authors' calculations

Furthermore, a strong relationship is observed from GHG emissions to primary energy consumption, indicating that environmental degradation significantly influences the country's energy choices. These results call for a revision of economic and energy policies in Tunisia, by promoting a growth model that is more environmentally sustainable, encouraging trade that incorporates environmental standards, and accelerating the energy transition through energy efficiency measures and the development of renewable energy, in order to reduce the impact of emissions on the national energy structure.

The diagnostic tests presented in Table 10 confirm the robustness and reliability of the estimated model. The Breusch-Godfrey statistic for residual autocorrelation (F = 0.236; P = 0.793) indicates the absence of serial correlation in the errors, ensuring the independence of the residuals. Heteroskedasticity tests, namely the Breusch-Pagan-Godfrey (F = 0.584; P = 0.757) and ARCH test (F = 1.759; P = 0.201), confirm homoscedasticity, i.e., the constancy of the residual variance, thereby strengthening the reliability of the coefficient estimates. Finally, the Jarque-Bera normality test (JB = 1.016; P = 0.601) shows that the residuals follow a normal distribution, a prerequisite for the validity of statistical inferences.

Finally, the Ramsey RESET specification test (F = 2.086, P = 0.174) indicates no evidence of functional form misspecification, suggesting that the model is correctly specified and that the included variables adequately capture the relationship under study. Overall, these results demonstrate that the model is statistically robust, stable, and suitable for analysing the determinants of CO_2 emissions. The CUSUM and CUSUM-squared stability tests further confirm that the model remains stable in both the short and long term, with the test statistics staying within the 5% confidence bounds. The graphical representation of these tests, shown in Figures 3 and 4, indicates that the estimated coefficients do not exhibit any significant structural breaks over the period 2009–2021.

Table 9: Results of the Granger causality test

Null hypothesis	F-Statistic	Prob
Log FMD does not Granger Cause Log EQ	1.083	0.364
Log EQ does not Granger Cause Log FMD	0.249	0.783
Log GDP does not Granger Cause Log EQ	2.911*	0.086
Log EQ does not Granger Cause Log GDP	0.633	0.545
Log ENG does not Granger Cause Log EQ	0.128	0.881
Log EQ does not Granger Cause Log ENG	15.554***	0.000
Log TO does not Granger Cause Log EQ	3.616*	0.052
Log EQ does not Granger Cause Log TO	0.153	0.860

*,** and ***denote significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' calculations

Table 10: Results of diagnostic and stability tests

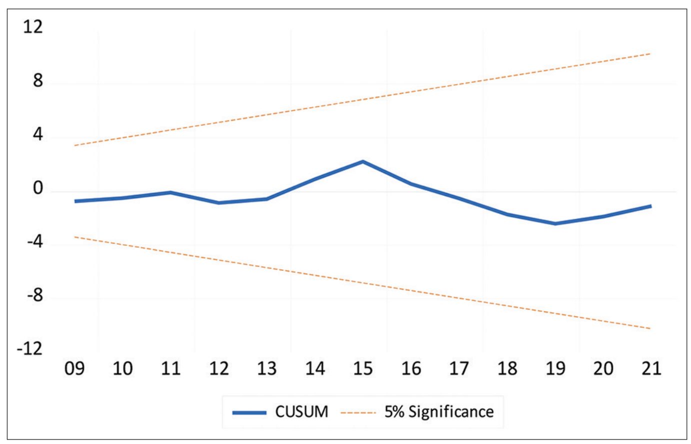
Diagnostic and stability tests	F-statistic	Prob. F (2,11)
Breusch-Godfrey Serial Correlation LM Test	0.236	[0.793]
Heteroskedasticity Test: Breusch-Pagan-Godfrey	0.584	[0.757]
Heteroskedasticity Test: ARCH	1.759	[0.201]
Jarque-Bera	1.016	[0.601]
Ramsey RESET Test	2.086	[0.174]

*,** and ***denote significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' calculations

Thus, the model parameters are temporally stable, which attests to the robustness and reliability of the econometric results obtained. In conclusion, these results highlight that economic growth and energy consumption are the main determinants of short-term emissions in Tunisia, whereas financial development, if directed towards environmentally sustainable investments, can contribute positively to environmental sustainability. The estimated model therefore appears statistically robust, stable, and relevant, reinforcing the validity of the findings and their usefulness for the design of effective environmental and financial policies. In addition to the previously presented diagnostic and stability tests, robustness checks were carried out by re-estimating the model equation using the FMOLS, DOLS, and CCR methods. The results of these estimations are summarised in Table 11 and compared with the long-term coefficients obtained from the ARDL model (Table 6).

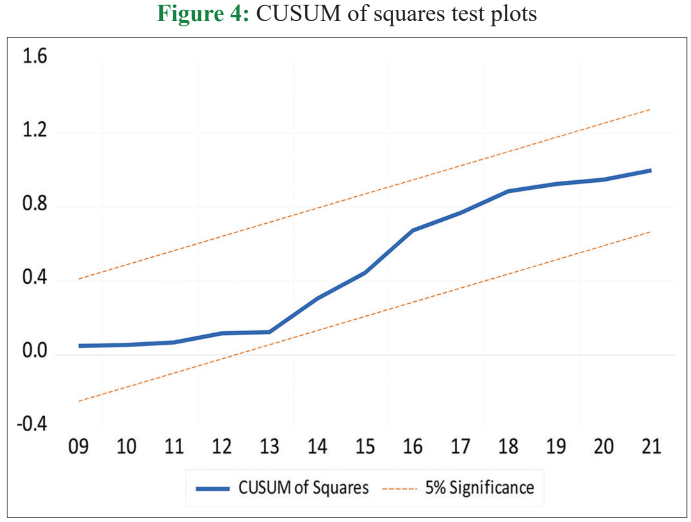
It is noteworthy that the estimates obtained from the FMOLS, DOLS, and CCR methods are consistent with those of the ARDL approach, thereby confirming the robustness of the results. As observed in the ARDL estimations, market-based financial development (Log FMD) contributes significantly to the improvement of environmental quality by reducing greenhouse

Figure 3: CUSUM test plots



Source: Authors' calculations

Figure 4: CUSUM of squares test plots



Source: Authors' calculations

Table 11: Estimations par FMOLS, DOLS et CCR

Variable	FMOLS	Prob.	DOLS	Prob.	CCR	Prob.
Log FMD	−0.036***	0.000	−0.045***	0.002	−0.036***	0.001
Log GDP	0.542***	0.000	0.519***	0.000	0.544***	0.000
Log ENG	2.427***	0.004	3.246**	0.014	2.407***	0.004
Log TO	−0.128*	0.064	−0.158*	0.082	−0.127*	0.065
C	−20.077***	0.000	−23.025***	0.000	−20.068***	0.000
R^2	0.946		0.981		0.947	
Adj. R^2	0.933		0.968		0.933	

*,** and ***denote significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' calculations

gas emissions. In contrast, economic growth (Log GDP) and energy consumption (Log ENG) have a positive and significant effect on emissions, thereby deteriorating environmental quality in Tunisia. External trade (Log TO) is found to be insignificant across the three estimation methods, indicating a limited or delayed impact on emissions. These findings confirm that financial development can serve as an effective lever for promoting environmental sustainability, while the management of economic growth and energy consumption remains essential to mitigating environmental pressures.

Furthermore, the R^2 values across all estimated models indicate that the total variation in greenhouse gas emissions is largely explained by the variables included in the model. For the ARDL model, the long-term R^2 is 0.981, showing that 98.1% of the variation in emissions is captured by the regressors, while the short-term R^2 of 0.866 also reflects a strong explanatory power over the immediate horizon. To verified robustness of our results, we employ Fully Modified Ordinary Least Square (FMOLS), Dynamic Ordinary Least Square (DOLS), and CCR. The reported that R^2 values range from 0.946 to 0.981, confirming the consistency and reliability of the outcomes across different specifications. These observations reinforce the validity of the conclusions, highlighting that financial development contributes to reducing emissions, whereas economic growth and energy consumption exert significant environmental pressure in Tunisia.

5. CONCLUSION AND POLICY IMPLICATIONS

In this study, we investigate the long-run relationship between financial development and the determinants of greenhouse gas (GHG) emissions in Tunisia over the period 2000–2021. We employ the autoregressive distributed lag ARDL approach, complemented by FMOLS, DOLS, and CCR estimators. The empirical findings indicate that market-based financial development contributes to reducing emissions, reflecting its ability to channel savings into green investments and stimulate innovation in clean technologies. However, our results show that the GDP per capita and primary energy consumption exert a significant positive effect on emissions, emphasizing that the carbon-intensive and fossil fuel-dependent nature of Tunisian economic growth.

Also, we indicate that the trade openness has a limited short-term effect but can play a key role in the transfer of clean technologies and the adoption of international environmental standards in the long term. Furthermore, we conclude that the Granger causality tests confirm that financial development has no direct effect on emissions, whereas GDP and trade openness exert a unidirectional causal influence on GHGs, and emissions. In turn affect primary energy consumption, illustrating the bidirectional relationship between energy choices and environmental degradation.

These findings underline the importance of directing financial flows towards sustainable projects, accelerating the energy transition through efficiency measures and renewable energy, and leveraging international trade to facilitate the adoption of clean technologies. Notably, the current study provides a robust empirical framework to inform public policies aimed at reconciling economic growth, environmental sustainability, and energy transition in Tunisia. The current study offers several significant policy implications for Tunisia's pursuit of sustainable development. Firstly, the government should prioritize the creation and expansion of green financial instruments, such as green bonds and ESG-compliant investment vehicles, to direct capital toward environmentally responsible sectors. Strengthening environmental regulations and institutional quality within the financial system is also crucial, guaranteeing that banks and financial institutions integrate climate risk assessments and carbon disclosures into their operations. Public-private partnerships (PPPs) can play a pivotal role in financing large-scale green infrastructure projects by combining private sector efficiency with public oversight. Furthermore, improving financial inclusion for small and medium enterprises engaged in green innovation can stimulate low-carbon entrepreneurship. Tunisia's monetary and fiscal authorities must also incorporate climate considerations into macroeconomic planning, using interest rates and tax incentives to encourage sustainable investments. Enhancing data transparency and monitoring mechanisms will enable more accurate tracking of greenhouse gas emissions related to financial activities, guaranteeing that financial development aligns with Tunisia's national climate targets of reducing emissions by 45% by 2030 and achieving climate neutrality by 2050. Finally, Tunisia should promote green and intelligent initiatives, such as remote work and smart infrastructure, to support eco-friendly practices. By improving sustainable investment, the Tunisia will reduce more the CO_2 emissions and ensures better environmental quality and advance long-term sustainable development.

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