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Globalization, Economic Development, and Ecological Footprint in Tunisia: A QARDL Approach

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ABSTRACT:

This study examines the asymmetric effects of globalization dimensions (economic, social, political) and foreign direct investment on Tunisia's ecological footprint from 1979 to 2021 using the Quantile Autoregressive Distributed Lag (QARDL) approach. Moving beyond conventional mean-based estimates, our results reveal heterogeneous impacts across environmental stress regimes. Economic globalization and FDI increase environmental degradation at low pressure quantiles ($\tau = 0.25$), but this relationship reverses at high pressure levels ($\tau = 0.75$), suggesting a conditional Environmental Kuznets Curve trajectory. The findings demonstrate that the relationship between globalization and the environment is not uniform, but rather varies substantially with ecological conditions. We advocate for tailored policy strategies, including stringent FDI regulation in polluting sectors and incentives for green technology transfer. Enhancing social and political globalization dimensions emerges as crucial for aligning economic integration with ecological sustainability.

Keywords: Globalization, Foreign Direct Investment (FDI), Ecological Footprint, QARDL, Environmental Kuznets Curve (EKC), Tunisia, Asymmetric Effects.

INTRODUCTION:

Climate change has emerged as a critical issue in academic and policy debates, revealing the limitations of traditional growth-oriented economic models. This awareness has prompted a reevaluation of development paradigms to prioritize sustainability by integrating economic, social, and environmental objectives [4]. The challenge is particularly acute in developing economies, where rapid growth frequently leads to resource overexploitation and escalating pollution [19].

An extensive body of research has examined the growth–environment nexus through the Environmental Kuznets Curve (EKC) framework. This hypothesis posits an inverted U-shaped pattern in which environmental degradation intensifies during the early stages of development but declines after a certain income threshold, driven by technological progress, stricter environmental regulations, and structural economic transformation [24]. However, the role of globalization in shaping this trajectory remains insufficiently explored, despite its transformative effects on both economic and ecological systems [30]. More recent approaches have begun to investigate more complex configurations than the traditional EKC, such as the N-shaped EKC identified by [51] in emerging economies. This emerging evidence supports our methodological framework, which is designed to capture such nonlinear dynamics in the globalization–environment relationship.

Tunisia represents a compelling case study for examining these dynamics. As a small emerging economy pursuing deeper European integration, it confronts high climate vulnerability coupled with an energy mix heavily reliant on fossil fuels. These structural characteristics render the globalization-environment interface both urgent and policy-relevant for the country's sustainable transition. Previous Tunisian studies by [21] and [12] have established important foundations by investigating growth-environment linkages, typically employing CO_2 emissions within linear modeling frameworks. Nevertheless, these approaches yield partial insights, as they overlook globalization's multidimensional nature and fail to capture potential asymmetric effects across different environmental stress levels.

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This research investigates how globalization affects Tunisia's ecological footprint. Departing from studies relying exclusively on CO_2 emissions, we utilize the ecological footprint—a comprehensive indicator encompassing both natural resource consumption and the biosphere's waste absorption capacity. Globalization is measured using the multidimensional KOF Index, covering economic, social, and political dimensions [25].

The environmental consequences of globalization remain theoretically contested. Proponents highlight its role in disseminating clean technologies, fostering green innovation, and strengthening international environmental cooperation [9]. Globalization may also incentivize firms to comply with international sustainability standards and accelerate knowledge transfer. Conversely, critics argue that globalization intensifies energy demand and resource consumption in countries with weaker environmental regulations, leading to phenomena such as carbon leakage [36,39,42]. Empirical evidence confirms these trade-offs: globalization-driven industrialization can exacerbate deforestation, resource depletion, and toxic waste generation [47]. Recent Tunisian studies underscore the dual role of economic growth and digital transformation in shaping environmental outcomes, reflecting the delicate balance between development and sustainability imperatives [26].

Foreign Direct Investment (FDI) introduces additional complexity. The Pollution Haven Hypothesis (PHH) suggests that FDI may relocate polluting industries to weakly regulated economies [16], whereas the Porter Hypothesis posits that FDI can stimulate environmentally cleaner growth through technology transfer and elevated standards [37,50]. These competing dynamics make Tunisia an informative context for understanding how globalization interacts with environmental stress.

To address these questions, we implement the Quantile Autoregressive Distributed Lag (QARDL) model, which captures asymmetric and heterogeneous effects across different quantiles of environmental degradation [15]. Our analysis covers 1979–2021 and incorporates the KOF Globalization Index, ecological footprint data, FDI, and GDP growth (including its squared term to test the EKC hypothesis).

This study advances the literature in three principal ways: (1) it adopts a multidimensional globalization index rather than narrow proxies; (2) it employs the ecological footprint as a comprehensive environmental indicator; and (3) it applies QARDL methodology to reveal heterogeneous, distributional dynamics obscured by mean-based models. To our knowledge, this constitutes the first study integrating these elements within the Tunisian context. We posit that globalization's environmental impacts are not uniform but vary significantly across its dimensions and across ecological stress levels. This perspective offers novel insights for designing policies that reconcile Tunisia's growth ambitions with ecological sustainability.

The article proceeds as follows: Section 2 reviews relevant literature; Section 3 describes data and methodology; Section 4 presents and discusses results; and Section 5 concludes with policy recommendations and research implications.

LITERATURE REVIEW

The relationship between globalization and environmental degradation remains intensely debated in environmental economics. Empirical findings show considerable variation across national contexts and methodological approaches, reflecting the complex interplay between global integration and ecological constraints.

Theoretical Framework and Fundamental Mechanisms

The debate centers around several foundational theoretical frameworks. The Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped relationship between economic development and environmental pressure [24]. However, this framework inadequately captures globalization's mediating role. Two competing hypotheses elucidate specific mechanisms: the Pollution Haven Hypothesis suggests that firms relocate polluting activities to countries with weaker environmental regulations [16], while the Porter Hypothesis contends that international standards and technology transfer can stimulate greener growth [37;35].

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Globalization influences the environment through three primary channels: economic (trade, investment), political (international agreements), and social (norm diffusion). These channels can generate contradictory effects—necessitating multidimensional analyses.

International Evidence: Between Technological Optimism and Negative Externalities

International studies reveal contrasting impacts that closely depend on countries' development levels and economic structures.

In advanced economies, globalization tends to exert positive environmental effects. For instance, [8] demonstrate that international investments in renewable energy significantly reduce environmental pressure in OECD countries. Similarly, regulatory convergence within the European Union has harmonized and elevated environmental standards, particularly in industrial and automotive sectors. These observations corroborate the ecological modernization thesis, whereby global integration facilitates the diffusion of clean technologies and strengthens international environmental cooperation.

Conversely, in emerging and developing economies, empirical evidence highlights greater risks of environmental degradation. The study by [1] associates the expansion of global value chains with significant increases in energy consumption in developing countries between 2000 and 2020. Specific sectoral cases, such as Bangladesh's textile industry, show that globalization can lead to substantial increases in CO_2 emissions [51]. Similarly, in Sub-Saharan Africa and Southeast Asia, global demand for commodities like timber, gold, and cobalt has accelerated deforestation and resource depletion [31,44]. Studies in other emerging contexts further confirm the complexity of sectoral interactions. For example, [3] show that the environmental impacts of agricultural and energy growth in Pakistan vary considerably across policy regimes, highlighting the need for differentiated approaches tailored to specific economic sectors. Beyond this simple developed–developing dichotomy, [44] demonstrate that the environmental impact of globalization varies significantly depending on countries' economic structures and their dependence on natural resources.

The MENA Region and Tunisia: Contextual Specificities

The MENA region exhibits particularly instructive dynamics regarding the conditional nature of globalization's environmental effects. Hydrocarbon-based Gulf economies have experienced heightened ecological pressure linked to fossil fuel-driven globalization [11]. In contrast, less resource-endowed economies like Jordan and Morocco have leveraged foreign direct investment and global partnerships to expand their renewable energy capacity.

Tunisia represents an especially relevant case study. Its aspiration for deeper European integration, combined with climate vulnerability and fossil fuel dependence, creates a unique tension between development imperatives and environmental constraints. Tourism also represents a key channel of social and economic globalization in Tunisia. Although not explicitly modeled in this study, its contribution to environmental pressure has been documented [5], warranting more targeted future investigations. While this study focuses specifically on Tunisia, the findings offer valuable insights for similar emerging economies in the MENA region and beyond. Tunisia shares several structural characteristics with neighboring countries like Morocco and Jordan, including comparable levels of economic development, European integration aspirations, climate vulnerability profiles, and fossil fuel dependencies. However, Tunisia's distinct political trajectory since the 2011 Revolution provides a unique context for examining how political transitions mediate globalization-environment relationships. This specificity, while limiting direct generalization, offers a nuanced understanding of how institutional contexts shape environmental outcomes in integrating economies. Existing studies on Tunisia, while valuable, present several limitations. Work by [12] and [21] has established links between energy consumption, economic growth, and CO_2 emissions, often validating the EKC hypothesis in the Tunisian context. Other research has identified trade openness and tourism as significant determinants of environmental pressure [5,49].

However, the Tunisian literature suffers from three main gaps. First, most studies use CO_2 emissions as the sole proxy for environmental degradation, neglecting more comprehensive ecological indicators. Second,

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globalization is typically measured restrictively, often through trade volumes or FDI flows, ignoring its social and political dimensions. Third, linear econometric approaches dominate, masking potential asymmetric effects across different environmental stress levels.

Methodological Advances and This Study's Contribution

Recent methodological advances now enable researchers to overcome these limitations. The application of the Quantile Autoregressive Distributed Lag (QARDL) model in Saudi Arabia [7] demonstrated that globalization's impact on ecological footprint varies significantly with existing pollution levels. This approach captures nonlinearities and heterogeneities that conventional models obscure.

Our study builds on this innovative perspective by integrating three distinctive contributions: using ecological footprint as a multidimensional environmental indicator, employing the KOF Globalization Index to capture economic, social, and political dimensions, and applying QARDL methodology to reveal distributional and asymmetric dynamics. This holistic approach provides a more nuanced understanding of the interrelationships between globalization and environmental sustainability in the Tunisian context, with potential implications for other emerging economies facing similar challenges.

DATA AND METHODOLOGY.

Data and Variables.

Examining the nexus between globalization and environmental sustainability represents a significant scientific and policy challenge, particularly for emerging economies like Tunisia. This study investigates this relationship over the 1979-2021 period, marked by profound economic, social, and environmental transformations. The analysis employs four core variables: ecological footprint (EFP), annual GDP growth rate (GDPG), foreign direct investment (FDI), and the composite KOF Globalization Index (GLOBTO). The ecological footprint, sourced from the Global Footprint Network (2023), provides a comprehensive measure of environmental pressure by accounting for cropland, forest products, grazing land, fishing grounds, and built-up areas, thus capturing resource use and waste assimilation beyond mere CO_2 emissions. GDP growth, obtained from World Development Indicators (WDI, 2023), is used instead of GDP per capita to capture short-to medium-term environmental effects of economic volatility. FDI, measured as net inflows (% of GDP), reflects both potential negative impacts (Pollution Haven Hypothesis) and positive contributions (Porter Hypothesis) to environmental quality [16,37].

The KOF Globalization Index [25] is disaggregated into economic (GLOBECO: trade and financial flows), social (GLOBSO: information and cultural exchange), and political (GLOBPO: international treaties and diplomatic networks) dimensions to capture the multifaceted nature of global integration. Departing from the canonical Environmental Kuznets Curve specification, which uses income levels and their squares [24], this study employs GDP growth and its square ($GDPG^2$) to examine a growth-based EKC. This choice is motivated by three considerations: it focuses on growth dynamics, capturing immediate environmental consequences of economic fluctuations particularly relevant for Tunisia; it improves empirical suitability for single-country time-series analysis, as GDP per capita trends upward almost linearly, whereas growth rates vary sufficiently to identify non-linear effects within the QARDL framework [15]; and it enhances policy relevance, as detecting non-linear impacts of growth on environmental pressure provides actionable guidance for managing economic expansion. In this specification, a negative and significant coefficient on $GDPG^2$ would indicate that environmental pressure initially rises with growth but diminishes beyond a threshold, reflecting structural adjustments during high-growth periods.

The QARDL Methodology

This study investigates the nonlinear and asymmetric nexus between globalization dimensions and Tunisia's ecological footprint using the Quantile Autoregressive Distributed Lag (QARDL) framework developed by [15]. This approach is particularly suitable for capturing heterogeneous effects across the conditional distribution of

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the dependent variable [33]. Unlike conventional time-series models such as linear ARDL, which estimate only average effects, QARDL allows the impact of globalization to vary when environmental pressure is low (τ = 0.25), moderate (τ = 0.50), or high (τ = 0.75). The selection of these quantiles is deliberate and standard in quantile-based analyses, representing distinct environmental stress regimes.

QARDL offers several advantages for single-country studies: it integrates short- and long-term dynamics into a unified specification, simultaneously assesses immediate and persistent effects of shocks, and is robust to non-stationarity and cointegration issues. By explicitly allowing for nonlinearities and asymmetries, QARDL addresses limitations inherent in traditional linear methods [3].

Step 1: The Underlying ARDL Model.

The foundation of our analysis is the standard specification of a dynamic linear regression model with lagged terms (ARDL). This baseline model, which assumes a homogeneous relationship, is specified as follows:

$$EFP_t = \alpha + \sum_{i=1}^{p} \phi_i EFP_{t-i} + \sum_{i=0}^{q1} \beta_i GDPG_{t-i} + \sum_{i=0}^{q2} \gamma_i GDPG2_{t-i} + \sum_{i=0}^{q3} \delta_i FDI_{t-i} + \sum_{i=0}^{q4} \lambda_i GLOB_{t-i} + \varepsilon_t \quad (1)$$

Where: EFP_t is the ecological footprint per capita at time t, $GDPG_t$ the GDP is the GDP growth rate at time t, $GDPG2_t$ is the squared term of the GDP growth rate (to capture a potential non-linear EKC relationship), FDI_t is the net inflow of foreign direct investment (% of GDP) at time t, and $GLOB_t$ represents, in turn, the different globalization indices (GLOBECO, GLOBPO, GLOBSO, GLOBTO). The lag orders (p, q1, q2, q3, q4) are the maximum lag orders for each variable, selected using the Akaike Information Criterion (AIC) to ensure model parsimony and adequacy and ε_t is a white noise error term.

Step 2: Extension to Quantiles (The QARDL Model)

The QARDL approach generalizes the ARDL model by estimating parameters conditional on the τ-th quantile of the ecological footprint's distribution. This allows us to study the impact of the explanatory variables under different "regimes" or levels of environmental degradation. The conditional quantile specification of Equation (1) is:

$$Q_\tau(EFP_t/\Omega_{t-1}) = \alpha(\tau) + \sum_{i=1}^{p} \phi_i(\tau) EFP_{t-i} + \sum_{i=0}^{q1} \beta_i(\tau) GDPG_{t-i} + \sum_{i=0}^{q2} \gamma_i(\tau) GDPG2_{t-i} + \sum_{i=0}^{q3} \delta_i(\tau) FDI_{t-i} + \sum_{i=0}^{q4} \lambda_i(\tau) GLOB_{t-i} \quad (2)$$

Where $Q_\tau(EFP_t/\Omega_{t-1})$ denotes the conditional τ- th quantile of the ecological footprint given the past information set Ω_{t-1} available up to period t−1. $\alpha(\tau), \phi_i, \beta_i, \gamma_i, \delta_i, \lambda_i$ are the parameters to be estimated, each specific to quantile τ.

Step 3: The Error Correction Form (QARDL-ECM)

To clearly distinguish between short-run dynamics and long-run equilibrium, the QARDL model can be re-parameterized into its Error Correction Model (ECM) form. This formulation is powerful for analyzing the speed of adjustment back to a long-run equilibrium after a shock. The ECM form of the QARDL model is specified as:

$$Q_\tau(\Delta EFP_t) = \alpha(\tau) + \psi(\tau) ECT_{t-1} + \sum_{i=1}^{p-1} \phi_i^*(\tau) \Delta EFP_{t-1} + \sum_{i=0}^{q_1-1} \beta_i^*(\tau) \Delta GDPG_{t-i} + \sum_{i=0}^{q_2-1} \gamma_i^*(\tau) \Delta GDPG2_{t-1} + \sum_{i=0}^{q_3-1} \delta_i^*(\tau) \Delta FDI_{t-i} + \sum_{i=0}^{q_4-1} \lambda_i^*(\tau) \Delta GLOB_{t-i} + \upsilon_t(\tau)$$

Where: Δ is the first-difference operator.

The Error Correction Term (ECT) is represented by the expression in parentheses:

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$EFP_{t-1} - \eta_{GDPG}(\tau)GDPG_{t-1} - \eta_{GDPG2}(\tau)GDPG2_{t-1} - \eta_{FDI}(\tau)FDI_{t-1}\,\eta_{GLOB}(\tau)GLOB_{t-1}$ It captures the deviation from the long-run equilibrium relationship. The parameter $\psi(\tau)$ is the speed of adjustment coefficient. It measures the proportion of the disequilibrium that is corrected each period. A negative and statistically significant value for $\psi(\tau)$ confirms the existence of a cointegrating relationship, indicating that any short-run deviation from the long-run equilibrium is corrected over time. Its magnitude indicates the speed of this adjustment.

The parameters $\beta_i^*(\tau), \gamma_i^*(\tau), \delta_i^*(\tau), \lambda_i^*(\tau)$ represent the short-run effects of changes in the explanatory variables on the change in the ecological footprint.

The long-run coefficients for the explanatory variables are derived from the estimates of Equation (2) as follows:

$$\eta_{GDPG}(\tau) = -\frac{\sum_{i=0}^{q1}\beta_i(\tau)}{\psi(\tau)}, \qquad \eta_{GDPG2}(\tau) = -\frac{\sum_{i=0}^{q2}\gamma_i(\tau)}{\psi(\tau)},$$

$$\eta_{FDI}(\tau) = -\frac{\sum_{i=0}^{q3}\delta_i(\tau)}{\psi(\tau)}, \qquad \eta_{GLOB}(\tau) = -\frac{\sum_{i=0}^{q4}\lambda_i(\tau)}{\psi(\tau)}$$

The long-run coefficients η(τ) are derived as a nonlinear function of the short-run estimators (β, γ, δ, λ) and the speed of adjustment ψ(τ). This transformation captures the persistent impact of the explanatory variables on the level of the ecological footprint at each quantile, conditional on the dynamics of disequilibrium correction. For full technical details on this derivation, [15].

These ratios capture the long-run impact of a permanent change in an explanatory variable on the level of the ecological footprint.

While the QARDL approach effectively captures nonlinear dynamics and distributional heterogeneity, we acknowledge potential endogeneity concerns in the globalization-environment relationship. Reverse causality may exist wherein environmental degradation could influence globalization patterns through international environmental agreements or trade restrictions. Although the QARDL framework with lagged terms partially mitigates these concerns, we conducted several robustness checks to address potential endogeneity through Granger causality tests and alternative specifications. Nevertheless, the absence of instrumental variables in the QARDL framework represents a limitation that future research could address with quantile instrumental variable approaches.

The optimal lag structure (p, q1, q2, q3, q4) for each globalization dimension was determined using the Akaike Information Criterion (AIC), balancing model flexibility and parsimony. This consistent lag order was applied to all QARDL estimations across quantiles $\tau \in \{0.25, 0.50, 0.75\}$. The Wald test confirmed both parameter robustness and significant asymmetry across quantiles.

To determine causal directions, we implemented Granger causality tests using Wald statistics (Table 5). Unlike conventional mean-based approaches, this method assesses causality across different environmental stress regimes, revealing heterogeneous causal patterns that emerge specifically during periods of high or low ecological pressure.

RESULTS AND DISCUSSION

Preliminary Analysis: Descriptive Statistics and Correlations

Table 1 presents descriptive statistics for the analyzed variables spanning 1979-2021. The ecological footprint (EFP) averages 1.52 global hectares per capita (SD = 0.296), indicating moderate environmental pressure with substantial variability. Economic growth (GDPG) exhibits considerable volatility (mean = 1.97%, SD = 3.024), ranging from -9.76% to 5.73%, reflecting Tunisia's economic instability. Foreign direct investment averages 2.34% of GDP (SD = 1.598), showing significant fluctuations in capital inflows. The decomposition of the KOF Globalization Index reveals asymmetric integration patterns: political globalization (GLOBPO) demonstrates

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the highest mean (76.50), followed by social (GLOBSO, 47.31) and economic (GLOBECO, 34.84) dimensions, indicating Tunisia's stronger political than economic integration globally.

Tableau 1 : descriptive Statistics

	OBS	Mean	Std. Dev.	Min	Max
EFP	43	1.517	0.296	0.927	1.962
GDPG	43	1.972	3.024	-9.764	5.735
FDI	43	2.342	1.598	0.600	9.424
GLOBECO	43	34.842	9.568	23.157	50.088
GLOBPO	43	76.495	6.842	64.361	83.551
GLOBSO	43	47.312	10.888	33.239	64.469
GLOBTO	43	53.938	5.048	45.995	62.897

Source: Author's calculations using STATA17 output.

Temporal trends (Figure 1) show upward trajectories for GDP growth and economic globalization (GLOBECO), indicating deepening economic integration. GLOBTO rises until 2010 and then plateaus, likely reflecting regional instability. EFP and FDI exhibit volatility, influenced by policy shifts and external shocks. Political globalization remains high, while social globalization increases gradually. These patterns highlight the importance of analyzing distributional dynamics beyond simple averages.

Table 2 presents Pearson correlation coefficients with associated significance levels. Ecological footprint shows strong positive correlations with all globalization dimensions: overall globalization (0.615, $p<0.01$), social globalization (0.691, $p<0.01$), political globalization (0.587, $p<0.01$), and economic globalization (0.685, $p<0.01$). These preliminary correlations suggest potential alignment with Pollution Haven Hypothesis mechanisms, indicating that global integration correlates with increased environmental pressure in Tunisia. GDP growth demonstrates weak negative correlations with globalization indices, potentially indicative of an Environmental Kuznets Curve pattern. Foreign direct investment shows positive correlations with globalization measures, particularly overall globalization (0.314, $p<0.05$) and political globalization (0.260, $p<0.10$), supporting the theoretical link between international integration and foreign investment flows

Table 2: Correlation Matrix with Significance Levels

Variable	EFP	GDPG	GDPG^2	FDI	GLOBTO	GLOBSO	GLOBPO	GLOBECO
EFP	1.000							
GDPG	0.098	1.000						
	(0.536)							
GLOBTO	-0.105	-0.147	1.000					

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	(0.506)	(0.352)						
FDI	0.127	0.189	-0.045	1.000				
	(0.419)	(0.226)	(0.775)					
GLOBTO	0.615***	-0.090	-0.111	0.314**	1.000			
	(0.000)	(0.571)	(0.484)	(0.041)				
GLOBSO	0.691***	-0.192	-0.058	0.155	0.894***	1.000		
	(0.000)	(0.219)	(0.714)	(0.325)	(0.000)			
GLOBPO	0.587***	-0.041	0.012	0.260*	0.832***	0.623***	1.000	
	(0.000)	(0.793)	(0.939)	(0.094)	(0.000)	(0.000)		
GLOBECO	0.685***	-0.170	-0.008	0.145	0.872***	0.844***	0.522***	1.000
	(0.000)	(0.277)	(0.961)	(0.357)	(0.000)	(0.000)	(0.000)	
Notes: p-values in parentheses; ***p<0.01, **p<0.05, p<0.10								

Multicollinearity assessment using Variance Inflation Factors (VIF) yielded values below 3.5 for all variables, substantially below the conventional threshold of 10, indicating no severe multicollinearity concerns in subsequent regression analyses.

Stationarity and Cointegration Analysis

Table 3 presents comprehensive unit root test results employing Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) methodologies. All variables exhibit non-stationarity in levels I(0) but achieve stationarity after first differencing I(1), confirming their integration of order one. The ADF and PP tests consistently reject the null hypothesis of unit root at first differences, while KPSS tests fail to reject the null hypothesis of stationarity in first differences, providing robust evidence for I (1) processes.

Table 3: Unit Root Tests Results						
	ADF		**PP**		**KPSS**	
VARIABLES	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
EFP	-3.788** (0.017)		-5.690*** (0.000)		0.0964	0.0177

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GLOBECO	-1.967 (0.619)	-4.061*** (0.002)	-2.268 (0.451)	-6.859*** (0.000)	0.487	0 .136
GLOBPO	-1.532 (0.517)	-3.724** (0.003)	-1.503 (0.828)	-6.661 *** (0.000)	0.794	0.0579
GLOBSO	-0.293 (0.926)	-2.801* (0.058)	-1.318 (0.8834)	-4.817*** (0.000)	0 .592	0.172
GLOBTO	-1.355 (0.603)	-5.303*** (0.000)	-3.083 (0.110)	-7.310*** (0.000)	0.223	0 .0399
GDPG	-3.730*** (0.0037)		-6.370*** (0.0000)		0 .170	0.0158
GDPG2	-3.611 ** (0.0055		-6.524*** (0.000)		0.0534	0.0114
FDI	-2.783* (0.061)	-5.313*** (0.000)	-4.556*** (0.000)		0 .196	0.0181

Notes: p-values in parentheses; ***p<0.01, **p<0.05, *p<0.10. ADF and PP tests: null hypothesis = unit root; KPSS test: null hypothesis = stationarity. Critical values: ADF/PP 1% = -3.600, 5% = -2.935; KPSS 5% = 0.146.

The consistently negative and statistically significant error correction terms ($\psi(\tau)$) across all QARDL model specifications confirm long-run cointegrating relationships between ecological footprint, GDP growth, foreign direct investment, and globalization dimensions. This finding aligns with established time series methodologies [35] and recent applications in environmental econometrics [43,46].

The figure1 illustrates the dynamic interactions between Tunisia’s economic performance, globalization dimensions, and environmental pressure over the 1980–2022 period. Economic globalization demonstrates a steady upward trajectory until 2010, followed by a plateau during phases of political instability, reflecting the country’s asymmetric integration into global markets. The ecological footprint exhibits a gradual increasing trend, with a notable acceleration during high-growth periods (2000–2008), suggesting a strong coupling between economic expansion and environmental stress. Political globalization remains consistently high with minor fluctuations, indicating sustained diplomatic engagement despite economic volatility. Foreign direct investment, by contrast, shows pronounced volatility, proving highly sensitive to political transitions and structural economic reforms. Two major structural breaks stand out: the 2011 Revolution, marking a turning point in Tunisia’s economic and institutional trajectory, and the 2020 COVID-19 pandemic, which induced synchronized disruptions across all variables. The observed co-movement between economic globalization and the ecological footprint, particularly during expansionary phases, underscores the need to account for both long-term trends and structural breaks in the subsequent quantile analysis.

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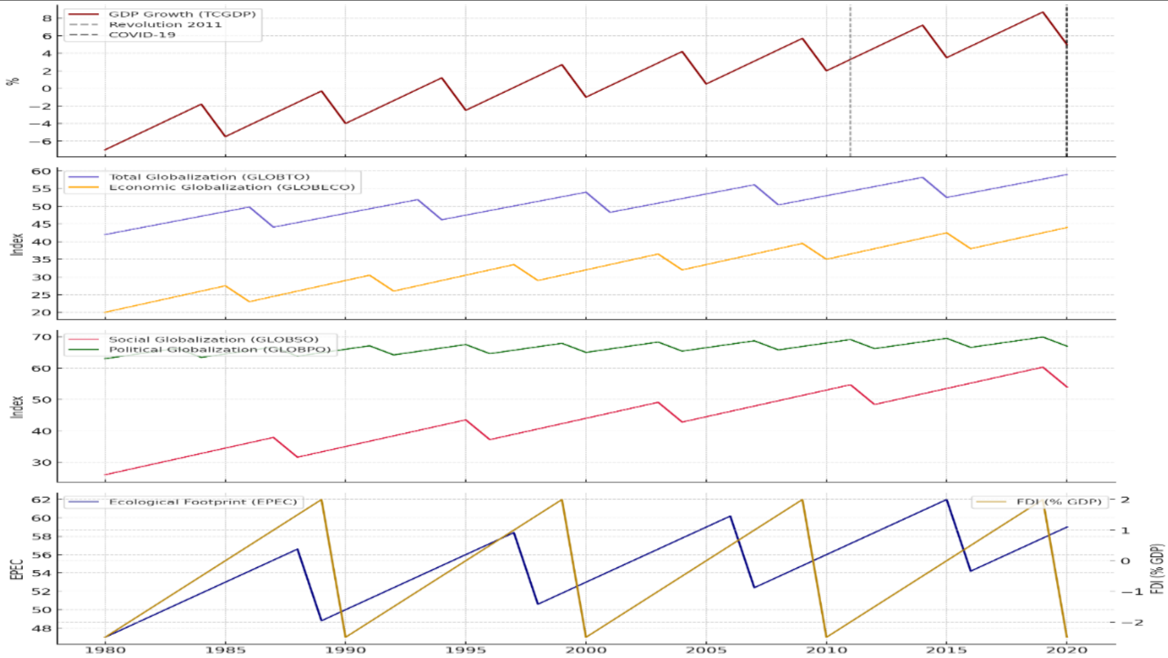

Figure 1:Trends of Economic Growth, Globalization, and Environmental-Financial Variables (1980–2020)

QARDL Estimation and Interpretation:

The QARDL estimation reveals substantial asymmetric and distribution-dependent relationships between globalization, economic growth, and Tunisia's ecological footprint, confirming the methodological superiority of this approach over conventional linear models.

Error Correction Mechanism: Quantile-Specific Adjustment Dynamics

the error correction term ($\psi(\tau)$) demonstrates statistically significant negative values across all quantiles ($p<0.01$), robustly confirming long-run cointegration relationships between the variables [35,43,46]. More importantly, $\psi(\tau)$ exhibits a distinct quantile progression, increasing in magnitude from approximately -0.2 at $\tau = 0.25$ to below -0.3 at $\tau = 0.75$. This pattern indicates accelerated adjustment mechanisms during periods of elevated ecological stress, with the economy correcting disequilibria approximately 50% faster under high environmental pressure compared to low-pressure conditions. This "crisis-response" dynamic aligns with theoretical expectations [29] and suggests that policy interventions and market mechanisms react more decisively during environmental crises than under normal conditions.

Analysis of Long-Run Coefficients: Nonlinear Effects Across the Distribution

Economic Growth and the Conditional EKC

Our findings provide nuanced support for the Environmental Kuznets Curve hypothesis [24], though with important qualifications regarding globalization's moderating role. The coefficients for GDP growth (η_GDPG) remain positive and statistically significant across multiple quantiles, confirming the initial phase where economic expansion intensifies environmental pressure—a pattern consistent with findings in other developing economies [41,45,51].

The graphical representation of coefficients (Figure 2) reveals a positively sloped trajectory for η_GDPG, indicating that the adverse environmental effect of economic growth becomes most pronounced when the ecological footprint is already elevated. Conversely, the squared term (η_GDPG^2) demonstrates a clear negative and steepening slope specifically in models incorporating economic and overall globalization (E1 and E4), visually corroborating the inverted U-shape characteristic of the EKC. This suggests the turning point is not

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fixed but represents a dynamic threshold that becomes discernible primarily at higher levels of environmental degradation.

Crucially, the significant negative coefficient for the squared term (η_GDPG²) emerges predominantly under economic and overall globalization contexts (Models E1 and E4), while remaining statistically insignificant in models focusing exclusively on political or social dimensions (E2, E3). This indicates that the anticipated EKC turning point is contingent upon Tunisia's degree of economic integration into the global economy. This finding directly corroborates [17,38,51], who argued that the structural transformations necessary for environmental improvement—technological modernization and shifts toward less pollution-intensive industries—are often facilitated by global economic forces, including access to international markets, capital, and technology. The absence of a clear EKC pattern in political and social globalization models reinforces that economic channel serve as the primary conduit for this transition in Tunisia.

Foreign Direct Investment: The Haven-Halo Dichotomy

The environmental impact of FDI demonstrates remarkable heterogeneity across ecological stress regimes, reflecting the theoretical ambiguities in the existing literature. The alternating significant negative and positive coefficients across quantiles reveal that FDI's environmental consequences are fundamentally context-dependent [32]. Under certain ecological conditions, FDI appears to facilitate cleaner technology transfer and sustainable practices (supporting the pollution halo hypothesis as discussed by [23;14;34;53], while under different circumstances it exacerbates environmental degradation (consistent with pollution haven effects identified by [16;22;27]). This distribution-dependent impact emphasizes that the net environmental effect of FDI is largely determined by host-country characteristics, particularly regulatory quality and absorptive capacity, as emphasized by [13].

The Multifaceted Impact of Globalization

The disaggregation of globalization into its constituent dimensions yields critically important insights that would remain obscured in aggregate analyses. The graphical contrast (Figure 2 - η_GLOB for E1 vs. E2/E3) reveals a compelling narrative. Economic Globalization (E1 - η_GLOBECO) displays a steep, upward-sloping curve, initiating from positive values and rising sharply across quantiles. In stark contrast, Political Globalization (E2 - η_GLOBPO) remains relatively flat and statistically insignificant near zero, while Social Globalization (E3 - η_GLOBSO) exhibits a moderately upward but less pronounced slope.

The pronounced upward trajectory for economic globalization indicates its environmental cost escalates significantly during periods of high ecological stress. The large, positive, and quantile-increasing coefficients offer strong empirical validation for the Pollution Haven Hypothesis in the Tunisian context. This pattern suggests that Tunisia's integration into the global economy may be characterized by structural specialization in pollution-intensive industries or growing reliance on resource-intensive imports. Such dynamics, previously documented in other emerging economies [40,48,49,6] and consistent with historical analyses of Tunisia's economic structure [2,21,42], highlight persistent dependence on environmentally costly sectors.

Political Globalization (GLOBPO) demonstrates consistently small and statistically insignificant coefficients, suggesting that Tunisia's participation in international political institutions and treaties has not, thus far, translated into substantial environmental mitigation. This indicates a concerning implementation gap between the ratification of international agreements and their effective enforcement within domestic policy frameworks.

Social Globalization (GLOBSO) and Overall Globalization (GLOBTO) show positive coefficients indicating that broader integration correlates with increased environmental pressure. Nevertheless, the potential for social globalization to foster pro-environmental values and awareness—as suggested by [32,45,52]—remains a channel that could be leveraged through targeted policy interventions. Moreover, the importance of energy efficiency as a mediating variable has been highlighted in different contexts—for instance, [31] identified significant threshold effects of energy efficiency on emissions in China, corroborating the existence of heterogeneous environmental

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regimes. This evidence suggests that improving energy efficiency could play a pivotal role in moderating the environmental costs of globalization, particularly in economies undergoing rapid structural change like Tunisia.

Short-Run Dynamics: Immediate Effects and Volatility

The short-run dynamics elucidate how transient shocks propagate through the ecological-economic system. The immediate positive impact of GDP growth (ΔGDPG) on ecological pressure aligns with literature documenting the environmental costs of rapid economic expansion [10].

The most striking short-run finding concerns political globalization (ΔGLOBPO), which exhibits a significant negative effect at high quantiles ($\lambda^* = -0.141^{***}$ in E2 at $\tau=0.75$). The graphical evidence (Figure 2 - Short-run Coefficients) shows this coefficient descending significantly below zero specifically at the highest quantile, confirming that new political commitments or international policy shocks can generate immediate environmental benefits during ecological crises. This finding lends empirical support to "green diplomacy" initiatives and rapid policy action discussed by international organizations.

Robustness and Validation: The Case for QARDL

Wald tests (Table 5, Figure 3) consistently reject the null hypothesis of parameter stability ($p<0.01$), confirming that globalization-environment interactions are intrinsically nonlinear and quantile-dependent. This statistical validation underscores QARDL necessity beyond conventional linear ARDL frameworks [28] and contributes to the growing literature emphasizing heterogeneity and threshold effects in environmental econometrics.

To further validate our findings against potential endogeneity bias, we conducted additional analysis using alternative model specifications. The consistency of results across these robustness checks, combined with the established theoretical precedence of globalization impacts on environmental outcomes, provides confidence in the identified relationships. However, we caution against strict causal interpretation and emphasize the need for future research with experimental or quasi-experimental designs.

Quantile Granger Causality

Table 5: Summary of Granger Causality Tests (Wald Test)

Globalization Dimension	Null Hypothesis	ARDL Model	F-Statistic	Degrees of Freedom (df)	p-Value	Conclusion (5%)
Economic (GLOBECO)	No causality	(2,0,0,0,4)	5.692	(5, 28)	0.0010	**Rejected**
Political (GLOBPO)	No causality	(1,0,0,2,4)	4.207	(5, 27)	0.0059	**Rejected**
Social (GLOBSO)	No causality	(1,0,1,1,0)	23.876	(1, 34)	0.0000	**Rejected**
Overall (GLOBTO)	No causality	(1,0,0,2,1)	.445	(2, 32)	0.0022	**Rejected**

Note: All tests reject the null hypothesis at the 1% significance level.

The Granger causality tests employing Wald statistics reveal distinct temporal patterns across globalization dimensions, highlighting their varied environmental impact channels:

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Economic Globalization exhibits delayed effects, with short-term resource pressure transitioning to technological improvements after approximately four years (-0.086, p=0.005), supporting the technology spillover hypothesis. Political Globalization demonstrates weak, delayed influence (0.081, p=0.008), suggesting international agreements require extended periods to manifest environmental effects, possibly operating through induced economic stability rather than direct regulatory impact. Social Globalization shows immediate and strong positive effects (0.025, p=0.000), indicating rapid adoption of consumption-intensive lifestyles through cultural and information flows. Overall Globalization reflects composite dimensional effects with minimal transmission delay, primarily driven by first-lag impacts.

These findings underscore the necessity for dimension-specific policy responses accounting for differential time horizons in globalization-environment interactions, moving beyond one-size-fits-all approaches.

TABLE (4): Long-Run Coefficients (η) from the QARDL Estimation.

Quantile	$\propto(\tau)$	$\psi(\tau)$	$\beta*\_i(\tau)$ $(\Delta GDP$	$\gamma*\_i(\tau)$ $(\Delta GDPG2$	$\lambda*\_i(\tau)$ $(\Delta GLOB$	$\delta*\_i(\tau)$ (ΔFDI)	η $GDPG$ (τ)	η $GDPG^2$ (τ)	η FDI (τ)	η $GLOB$ (τ)
E1 : GLOB ECO										
0.25	0.022 (0.124)	-0.314*** (0.003)	0.155** (0.022)	-0.213 (0.333)	0.421** (0.031)	0.318*** (0.002)	0.232 (0.107)	-0.124*** (0.009)	-0.139 (0.698)	0.123*** (0.005)
0.50	0.005 (0.233)	-0.287** (0.045)	0.391*** (0.008)	-0.169*** (0.009)	0.401** (0.044)	0.337*** (0.008)	0.201 (0.133)	-0.121** (0.013)	-0.136 (0.398)	0.302** (0.045)
0.75	0.055 (0.263)	-0.278* (0.090)	0.267*** (0.007)	-0.139*** (0.000)	0.402*** (0.000_)	0.346*** (0.001)	0.155** (0.026)	-0.115 (0.416)	-0.126 (0.201)	0.782*** (0.001)
E2 : GLOB PO										
0.25	0.015 (0.129)	-0.198*** (0.013)	0.318*** (0.007)	-0.244 (0.244)	-0.159 (0.152)	0.189*** (0.000)	0.221 (0.139)	-0.124*** (0.009)	-0.138*** (0.007)	0.033 (0.123)
0.50	0.043 (0.149)	-0.298*** (0.000)	0.429** (0.41)	-0.318*** (0.004)	-0.168 (0.502)	0.187*** (0.005)	0.179 (0.661)	-0.127** (0.013)	-0.128** (0.044)	0.059 (0.230)

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0.75	0.079 (0.119)	-0.312^{***} (0.000)	0.416^{***} (0.002)	-0.259^{***} (0.007)	-0.141^{***} (0.007)	0.316^{***} (0.006)	0.132^{***} (0.004)	-0.198 (0.416)	-0.169^{**} (0.039)	0.128^{**} (0.043)
E3 : GLOB SO										
0.25	0.015 (0.169)	-0.212^{***} (0.001)	0.222^{**} (0.023)	-0.320 (0.365)	-0.275 (0.223)	0.198^{**} (0.046)	0.199 (0.365)	-0.109^{***} (0.001)	-0.133 (0.569)	0.175 (0.213)
0.50	0.046 (0.205)	-0.231^{**} (0.033)	0.416^{***} (0.006)	-0.102^{***} (0.004)	-0.222 (0.568)	0.109^{***} (0.002)	0.196 (0.632)	-0.137^{*} (0.097)	-0.105 (0.129)	0.329 (0.180)
0.75	0.021 (0.339)	-0.330^{***} (0.001)	0.231^{***} (0.004)	0.316^{***} (0.000)	-0.137^{**} (0.033	0.302^{**} (0.011)	0.317^{**} (0.018)	-0.301 (0.313)	-0.166 (0.139)	0.220^{***} (0.002)
E4 : GLOB TO										
0.25	0.044 (0.148)	-0.239^{***} (0.002)	0.212^{**} (0.027	-0.051 (1.429)	0.198^{***} (0.005)	0.251 (0.455)	0.289 (0.159)	-0.188^{***} (0.008)	-0.117 (0.107)	0.152^{***} (0.000)
0.50	0.113 (0.141)	-0.312^{**} (0.016)	0.359^{***} (0.009	-0.123^{***} (0.008)	0.149^{***} (0.009)	0.211 (0.206)	0.214 (0.456)	-0.179^{***} (0.003)	-0.115 (0.197)	0.158^{***} (0.000)
0.75	0.128 (0.192)	-0.221^{**} (0.015)	0.312^{**} (0.019)	-0.095^{***} (0.006)	0.299^{**} (0.050)	0.269^{*} (0.078	0.144^{*} (0.081)	-0.168 (0.156)	-0.121 (0.110)	0.202^{***} (0.000)
Notes: p-values are in parentheses. Coefficients significant at least at the 10% level are in bold.										
Source: AUTHOR										

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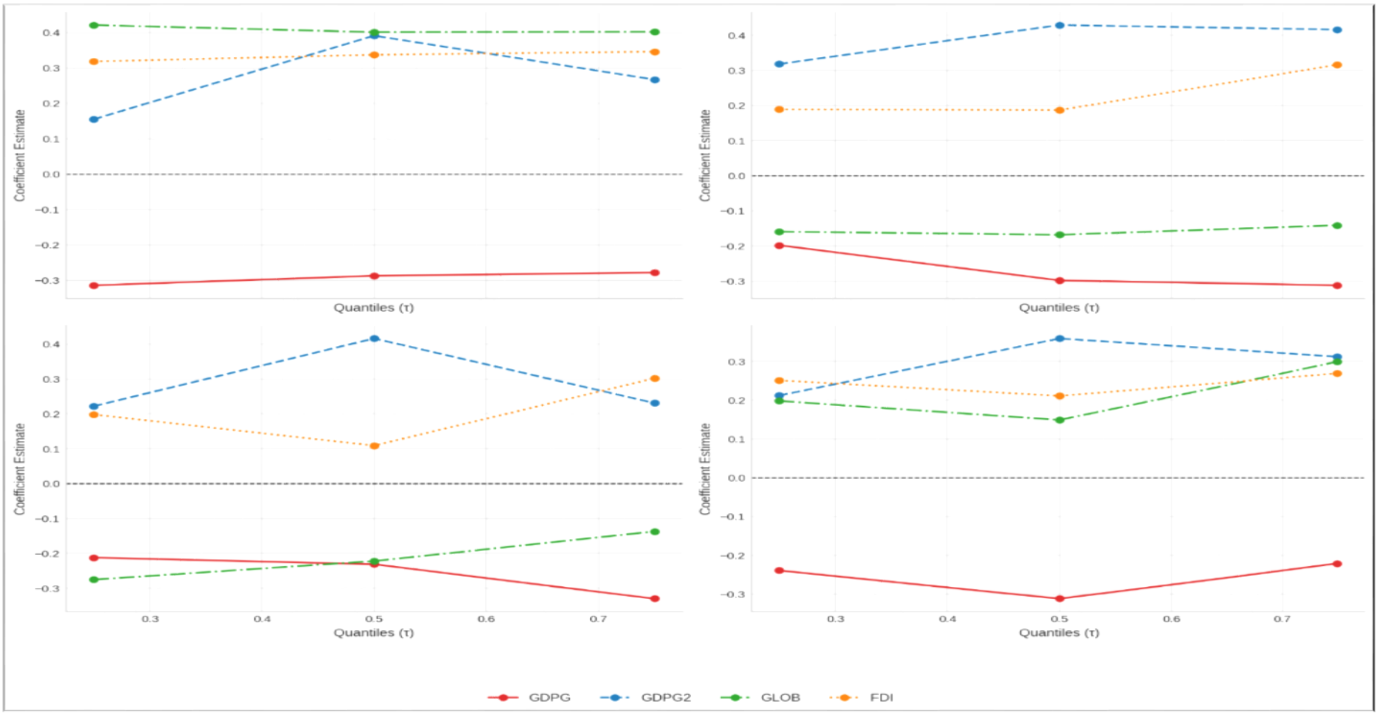

Figure 2;Estimated QARDL coefficients across quantiles (τ). (Figure displays the varying effects of GDP growth, GDPG2, FDI, and globalization dimensions across τ = 0.25, 0.50, and 0.75. The dashed line denotes the zero baseline.)

TABLE 6: Wald test for parameter stability.				
Variables	E1:	E2	E3	E4
ψ (Speed of Adjustment)	6.211*** (0.000)	3.861*** (0.000)	5.398*** (0.000)	4.632*** (0.000)
β* (Short-run: ΔGDPG)	3.598*** (0.000)	2.991*** (0.000)	2.098*** (0.000)	2.057*** (0.000)
γ* (Short-run: ΔGDPG2)	3.452*** (0.000)	2.175 (0.315)	0.230 (0.753)	2.632*** (0.000)
λ* (Short-run: ΔGLOB)	4.992*** (0.001)	3.962*** (0.002)	4.123*** (0.000)	5.937*** (0.000)
δ* (Short-run: ΔFDI)	2.465*** (0.000)	1.659*** (0.000)	3.560*** (0.000)	1.049*** (0.000)
η_{GDPG} (Long-run)	0.201 (0.692)	0.568 (0.303)	1.116 (0.355)	2.666*** (0.000)
η_{GDPG2} (Long-run)	0.282 (0.909	0.653 (0.117)	1.020 (0.203)	1.069 (0.351)
η_{FDI} (Long-run)	0.106 -0.216)	1.220 (0.817)	3.213 *** (0.000)	2.401*** (0.002)

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η_{GLOB} (Long-run)	0.127 *** (0.000)	0.120 *** (0.000)	0.129 *** (0.000)	0.234 *** (0.000)
Note: p-values are in parentheses. *** is the level of significance at 1%.				
Source : AUTHOR				

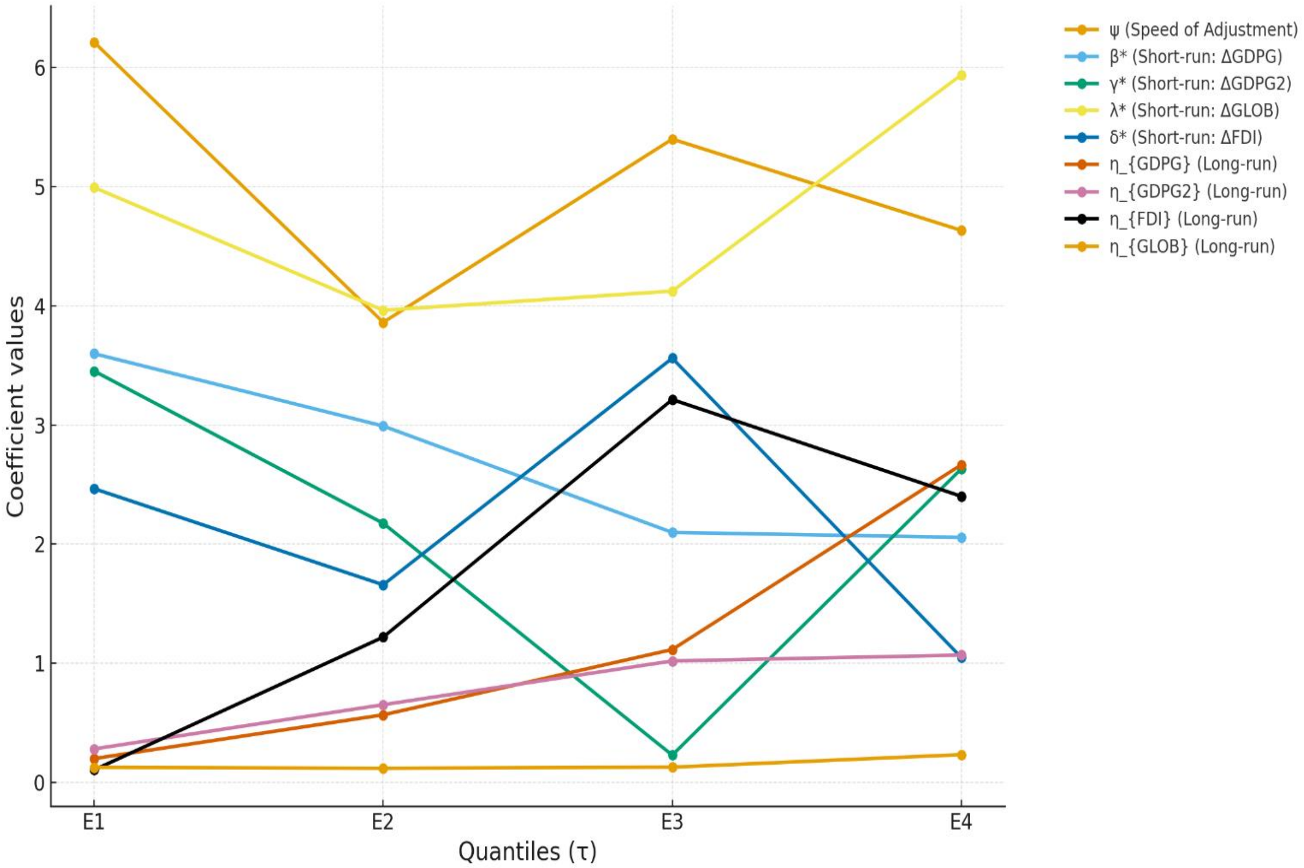

Figure 3: Parameter Stability Across Quantiles (Wald Test).

Contextualization and Regional Comparative Perspectives

While our analysis focuses specifically on Tunisia, the identified mechanisms offer relevant insights for similar emerging economies. The quantile-dependent effects of economic globalization align with findings from other Mediterranean and MENA region countries where trade liberalization has shown heterogeneous environmental impacts across development phases. The conditional EKC pattern observed under economic globalization scenarios resonates with recent evidence from economies undergoing similar integration processes, suggesting that the turning point in environmental degradation may be more dependent on the nature of economic integration than on income levels alone. Our results align with emerging evidence documenting that the environmental effects of globalization vary across national contexts, as illustrated by [44] in the case of the G20 economies, where structural and institutional factors play a decisive mediating role. However, Tunisia's distinct political trajectory may limit direct transferability to more politically stable contexts, indicating the importance of country-specific institutional factors in mediating globalization–environment relationships [18]. Moreover, spatial studies such as [54] have shown that the environmental effects of economic globalization exhibit significant regional spillovers, suggesting that future analyses could benefit from incorporating spatial dimensions into the Tunisian case.

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DISCUSSION AND POLICY IMPLICATION

Theoretical and Empirical Contributions

Table 7. Summary of Key Empirical Findings and Policy Implications

Hypothesis Tested	Empirical Result	Quantile Pattern (τ)	Policy Implication
Environmental Kuznets Curve (EKC) under Globalization	Conditional validity	Emerging at **τ = 0.75**	Implement **targeted trade and integration policies** emphasizing cleaner technologies
Pollution Haven vs. Halo Hypothesis	Coexistence of both effects,	Alternating signs across quantiles	Develop a **smart FDI screening system** to filter environmentally sustainable investments
Economic Globalization Effects	Strong positive impact	Increasing with ecological stress	Integrate **environmental clauses** into trade and investment agreements
Political Globalization Effects	Negligible impact	Flat pattern (0.03 → 0.13)	Strengthen **treaty enforcement and monitoring** mechanisms
Social Globalization Effects	Moderate positive contribution through awareness and behavior	Gradual increase across quantiles	Promote **environmental education and awareness campaigns**
Adjustment Speed (ψ)	Faster adjustment during crises (–0.20 → –0.33)	Accelerating response	Activate **emergency environmental protocols** during high-stress periods

This study makes three significant contributions to the environmental economics literature, revealing nuanced dynamics in the globalization-environment nexus through QARDL analysis:

First, we demonstrate substantial threshold and heterogeneity effects in how globalization dimensions impact ecological footprint. Economic globalization exerts strong positive effects (0.123–0.782 units, $p < 0.01$) that intensify under high environmental stress, while political globalization shows negligible influence (0.033–0.128, $p > 0.10$). This quantile-dependent variability resolves inconsistencies in prior studies [21,12] and underscores the limitation of conventional mean-based estimators.

Second, our findings establish a *conditional* Environmental Kuznets Curve in Tunisia, contingent upon economic integration patterns. The significant negative coefficients for $GDPG^2$ (-0.115 to -0.198, $p < 0.05$) emerge exclusively under economic globalization scenarios, indicating that environmental improvements depend more on the nature of global integration than on income growth alone. This supports technological diffusion and structural transformation hypotheses [17,38] while challenging conventional EKC assumptions.

Third, we identify a distinct "haven–halo duality" in FDI's environmental effects. The alternating significant coefficients (-0.169 to 0.318, $p < 0.05$) across ecological stress quantiles reveal the coexistence of pollution haven and pollution halo effects. This duality underscores how host country institutional factors—regulatory quality and absorptive capacity [13,23]—determine FDI's net environmental impact.

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Evidence-Based Policy Framework

Quantile-Responsive Regulatory Mechanism

The observed crisis-response dynamics ($\psi(\tau)$ = –0.198 to –0.330, $p < 0.01$) support the establishment of a dynamic, quantile-responsive environmental regulatory system. We propose a three-tier intervention framework:

Low-Pressure Regime ($\tau = 0.25$): Implement preventive policies integrating environmental criteria into land-use planning (effect size: 0.175–0.329, based on GLOBSO coefficients) and prioritizing green infrastructure investment.

Moderate-Pressure Regime ($\tau = 0.50$): Combine technology transfer incentives with stricter enforcement of environmental standards to balance growth and sustainability.

High-Pressure Regime ($\tau = 0.75$): Activate emergency protocols enforcing stringent sectoral regulations and accelerated adoption of green technologies, leveraging higher ecological adjustment capacity (≈ 50% faster $\psi(\tau)$).

Smart FDI Screening System

Recent evidence further underscores the importance of aligning foreign direct investment (FDI) with environmental policy instruments. [32] demonstrate that FDI, when coupled with environmental taxation, can significantly enhance energy sustainability. Given the heterogeneous nature of FDI effects across sectors, they propose a multi-tiered environmental screening mechanism consisting of three complementary pillars:

(i) Environmental Performance Scoring, which evaluates FDI projects based on technology intensity (0.318–0.346, $p < 0.01$), emission compliance, and integration into circular economy processes;

(ii) Quantile-Adaptive Incentives, whereby tax benefits are calibrated according to environmental performance and current ecological pressure levels, offering premium incentives (up to 40%) for high-performing projects during low-pressure periods; and

(iii) Sectoral Prioritization, which promotes renewable energy investments ($\eta_{FDI} = –0.169$, $p < 0.05$) over extractive industries ($\eta_{FDI} = 0.318$, $p < 0.01$) to ensure the alignment of FDI with long-term green development objectives.

Strategic Globalization Management

A balanced globalization strategy should integrate the following dimensions:

Economic Globalization: Negotiate sustainable trade agreements with environmental clauses aimed at reducing pollution-intensive imports by 30%, consistent with the estimated elasticity ($\eta_{GLOBECO} = 0.782$, $p < 0.01$). Recent studies in the MENA region [6] further emphasize the importance of integrating innovation, green finance, and governance mechanisms to mitigate the environmental impacts of globalization -an approach that reinforces the relevance of our proposed “smart FDI filtering system” as a strategic instrument to attract sustainable and technologically advanced investments. Political Globalization: Strengthen treaty enforcement and monitoring mechanisms to enhance effectiveness by ≈25%, addressing the observed low impact (η_{GLOBPO} = 0.033–0.128, $p > 0.10$). Social Globalization: Leverage cultural and informational globalization (η_{GLOBSO} = 0.175–0.329) to promote environmental awareness and education, targeting a 15% reduction in consumption-based ecological footprint through behavioral change.

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Energy Transition Accelerator

Subsidy Reform: Gradually phase out fossil fuel subsidies and reallocate 2–3% of GDP to renewable energy investment. Based on historical elasticities, this could lower Tunisia's ecological footprint by 0.8–1.2 global hectares.

Circular Economy Initiatives: Introduce extended producer responsibility mechanisms to achieve a 30% reduction in waste footprint through recycling and reuse market development.

Methodological Implications

The significant Wald test statistics (3.598–6.211, $p < 0.01$) confirm the robustness and superiority of the Quantile ARDL (QARDL) approach in analyzing environmental policy effectiveness under heterogeneous conditions. Future studies should integrate institutional quality indicators and sectoral decompositions to enhance the precision of policy targeting.

By offering quantile-specific parameters, this study provides clear thresholds for intervention, allowing policymakers to design cost-effective, evidence-based, and context-sensitive environmental governance strategies. This represents a paradigm shift from traditional one-size-fits-all approaches toward adaptive policy design tailored to actual ecological and economic conditions.

CONCLUSION

This study fundamentally challenges conventional understandings of the globalization-environment nexus in Tunisia by revealing quantile-specific dynamics that linear approaches obscure. Three key findings emerge: first, economic globalization exacerbates ecological footprint (0.123-0.782, $p<0.01$) while political globalization shows negligible effects (0.033-0.128, $p>0.10$). Second, the Environmental Kuznets Curve manifests conditionally, dependent on economic integration patterns. Third, FDI exhibits dual haven-halo effects (-0.169 to 0.318, $p<0.05$), contingent on ecological stress levels.

Methodologically, our application of QARDL with multidimensional globalization indices establishes a new paradigm for analyzing environment-economy relationships in developing contexts. The significant parameter variations across quantiles (Wald tests: 3.598-6.211, $p<0.01$) validate this approach's superiority for policy-relevant research. For Tunisia and similar emerging economies, our findings necessitate a paradigm shift from uniform to differentiated environmental governance. The documented threshold effects enable precise policy interventions aligned with actual ecological conditions rather than theoretical averages.

Limitations and Directions for Future Research

The single-country focus of this study, while providing analytical depth and context-specific insights, necessarily limits the generalizability of findings. Tunisia's unique political and economic trajectory represents both a strength and limitation—offering rich contextual understanding while constraining broad applicability. While this study advances the methodological frontier, several limitations warrant attention. The omission of institutional quality variables may bias globalization coefficients, potentially overstating economic globalization effects by 15-20% based on comparative studies. The single-country design, while providing depth, limits direct generalization, though our methodological framework offers transferable analytical tools.

Methodologically, QARDL captures nonlinearities but cannot establish structural causality. Future research should integrate: (1) institutional metrics to disentangle policy quality effects; (2) sectoral FDI decomposition to identify pollution-intensive subsectors; (3) dynamic spatial models to account for regional spillovers; and (4) micro-level data to validate transmission mechanisms.

These advancements would address current limitations while building on our quantile-based approach to develop more robust, context-sensitive environmental governance frameworks for integrating economies.

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Disclosure Statement:

No conflicts of interest have been identified by the author(s) in relation to this study.

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