

Nonlinear and Threshold Effects of Internet Access: Evidence from North Africa

الآثار غير الخطية وتأثيرات العتبة للوصول إلى الإنترنت: أدلة من شمال أفريقيا

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Abstract: This study examines the non-linear relationship between internet penetration and economic growth in North Africa, challenging the assumption of a universal digital dividend. Using a fixed-effects panel model for Algeria, Egypt, Libya, Morocco, and Tunisia (2000-2023), we find no significant linear effect. Instead, the relationship follows a U-shaped curve, with a threshold at approximately 33.7% penetration. Below this level, the growth impact is non-positive; above it, the effect becomes positive. Furthermore, the economic return to digital infrastructure is strongly conditioned by urbanization, with a significant positive interaction effect indicating that urban agglomerations amplify the benefits of connectivity. These results suggest that the digital dividend in the region is not automatic but contingent on achieving critical mass and complementary structural factors, notably urban development. The study provides novel empirical evidence for a threshold-based model of digital growth in North Africa, offering nuanced insights for policymakers to design phased and spatially informed digital development strategies.

Keywords: Internet access, Economic growth, Nonlinear effect, Threshold effect, North Africa.

المخلص: تبحث هذه الدراسة في العلاقة غير الخطية بين انتشار الإنترنت والنمو الاقتصادي في منطقة شمال أفريقيا، متحدياً بذلك الافتراض القائل بوجود عائد رقمي شامل وموحد. ومن خلال استخدام نموذج بيانات السلاسل الزمنية المقطعية (Panel Data) ذات التأثيرات الثابتة لدول الجزائر ومصر وليبيا والمغرب وتونس خلال الفترة الممتدة من عام 2000 إلى عام 2023، لم تتوصل الدراسة إلى وجود أثر خطي ذي دلالة إحصائية. وعوضاً عن ذلك، تبين أن العلاقة تتخذ شكل منحنى حرف (U)، حيث توجد عتبة فاصلة عند مستوى انتشار يقارب 33.7%. وفي حين يكون تأثير النمو غير إيجابي دون هذا المستوى، فإنه يتحول إلى تأثير إيجابي بمجرد تجاوزه. وعلاوة على ذلك، فإن العائد الاقتصادي للبنية التحتية الرقمية مرهون بشكل قوي بمستوى التحضر، إذ يشير التأثير التفاعلي الإيجابي والملاحظ إحصائياً إلى أن التجمعات الحضرية تعمل على تعظيم فوائد الاتصال الرقمي. وتُشير هذه النتائج إلى أن العائد الرقمي في المنطقة ليس

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تلفائياً، بل هو مشروط بتحقيق كتلة حرجية وتوفير عوامل هيكلية مكتملة، لا سيما التنمية الحضرية. وتقدم هذه الدراسة أدلة تجريبية جديدة تدعم نموذج النمو الرقمي القائم على العتبة في شمال أفريقيا، موفرة بذلك رؤى دقيقة لصناع السياسات لتصميم استراتيجيات تنمية رقمية مرحلية ومراعية للأبعاد المكانية. الكلمات المفتاحية: الوصول إلى الإنترنت، النمو الاقتصادي، التأثير غير الخطي، تأثير العتبة، شمال أفريقيا.

1. Introduction

The global economy is increasingly shaped by digital technologies, with internet access widely regarded as a critical driver of productivity, innovation, and economic growth. This assumption underpins the “digital dividend” hypothesis, a concept suggesting that the adoption of digital technologies yields tangible economic returns (Peng & Dan, 2023). Specifically, this hypothesis posits that investments in information and communication technology (ICT) infrastructure will translate directly into accelerated economic development (Du & Wang, 2024). Consequently, bridging the digital divide, defined as the gap in access to and use of digital technologies, has become a central goal for policymakers worldwide, particularly in developing regions.

The North African region presents a compelling yet understudied case for examining this hypothesis. Countries such as Algeria, Egypt, Libya, Morocco, and Tunisia have undertaken significant efforts to expand digital infrastructure over the past two decades. However, their economic trajectories have been heterogeneous and influenced by factors including political instability, reliance on hydrocarbons, and varied structural reform agendas. Preliminary data reveals a rapid but uneven rise in internet penetration alongside volatile and often modest economic growth rates. This juxtaposition raises a critical question: has the expansion of the digital economy in North Africa yielded the expected growth dividend, or does it reflect the “productivity paradox” or “third-level divide” observed in other developing contexts, where access does not guarantee positive outcomes (Van Deursen & Helsper, 2015; Haftu, 2019)?

Existing empirical literature offers mixed guidance. While numerous studies document positive impacts of ICT on growth in advanced and some emerging economies, other research highlights a “productivity paradox,” where significant

technological investment fails to produce commensurate macroeconomic gains. This paradox is often attributed to time lags, measurement issues, or, most pertinently, a lack of complementary assets such as human capital, efficient institutions, and appropriate regulatory frameworks. The specific dynamics in the North African context, with its unique socioeconomic and institutional characteristics, remain insufficiently studied. Most regional studies are either descriptive or focus on single countries, lacking a comparative, econometric analysis that accounts for non-linearities and conditioning factors.

This study aims to fill this gap by rigorously investigating the relationship between internet penetration and economic growth in North Africa from 2000 to 2023. It moves beyond the linear model to test for a non-linear, threshold-based relationship and examines whether the impact of digital infrastructure is conditional on the level of urbanization—a key structural characteristic and proxy for agglomeration economies and the availability of complementary services. The analysis employs a fixed-effects panel regression model on data from five North African countries. The core findings challenge the simplistic digital dividend narrative. First, we find no statistically significant linear relationship between internet penetration and Gross Domestic Production (GDP) growth. Second, the relationship follows a significant U-shaped pattern, with a calculated turning point at approximately 33.7% internet penetration. Third, we identify a strong positive interaction effect between internet penetration and urbanization, indicating that the economic returns to digital infrastructure are significantly amplified in more urbanized settings.

The contributions of this research are threefold. First, it provides novel empirical evidence on the non-linear and contingent nature of the digital-growth nexus in a region where such analysis is scarce. Second, it identifies a specific policy-relevant threshold for internet penetration. Third, it underscores the critical role of urbanization as a complementary factor, offering nuanced insights for regional development strategies. The paper proceeds as follows: Section 2 reviews the

relevant literature, Section 3 outlines the methodology and data, Section 4 presents the empirical results, Section 5 discusses the findings and implications, and Section 6 concludes.

2. Literature Review

2.1 .The Theoretical Landscape: From Access to Complementarities

The academic discourse on technology and growth has evolved significantly. Early optimism, rooted in endogenous growth theory, viewed technology as a key engine for productivity. The concept of the “digital divide” initially focused on gaps in physical access to technology. However, scholarly understanding has deepened to recognize subsequent divides in the use and impact of technology. This evolution is often conceptualized as a progression from the first-level (access), to the second-level (skills and usage), and finally to the third-level divide, which pertains to disparities in the tangible outcomes or benefits derived from internet use (Van Deursen & Helsper, 2015; Van Dijk, 2012). A central theoretical framework for understanding these outcome disparities is the complementary assets theory (Teece, 1986). This theory posits that the economic returns to new technologies are not inherent but are contingent on the presence of complementary factors, such as human capital, institutional quality, and physical infrastructure. In the context of developing economies, urbanization is often a critical complementary asset. It consolidates the markets, skilled labor, and service networks necessary both for technology adoption and for translating digital usage into tangible innovation and growth (Dasgupta, Lall, & Wheeler, 2001).

2.2. Global Empirical Evidence: Linear, Non-Linear, and Contingent Effects

Empirical evidence on the ICT-growth relationship is heterogeneous. A body of research, primarily focusing on developed nations, finds positive linear effects. However, a parallel strand, often concerning developing economies, documents insignificant or even negative initial effects—a modern manifestation of the “productivity paradox.” This has led to investigations into non-linear relationships. A growing

body of research identifies threshold effects or U-shaped patterns where benefits materialize only after a critical mass of adoption is achieved. For instance, studies in Sub-Saharan Africa have found thresholds as low as 3.55% for general internet access (Abdulqadir & Asongu, 2022) and 60% electrification rate for fixed broadband (Kouam & Asongu, 2023). Others report inverted U-shaped (Nguyen et al., 2022) or downward U-shaped patterns (Rangkakulnuwat & Dunyo, 2018), indicating significant heterogeneity across contexts. This evidence suggests that the search for a universal, linear digital dividend is likely misplaced. This diversity of findings underscores that the relationship between ICT and growth is highly context-dependent and rarely linear.

Furthermore, a growing literature tests conditional effects, demonstrating that ICT's impact is moderated by the availability of complementary factors, as predicted by complementary assets theory. Among these factors, urbanization has been identified as a significant moderator. Research in the European Union and the Organization of Islamic Countries finds that the economic return to broadband or ICT is amplified in more urbanized settings, highlighting a synergistic relationship between digital and physical agglomeration (de Clercq, D'Haese, & Buysse, 2023; Hussain, Li, Yang, & Sohail, 2024). This observed synergy forms a key hypothesis for the present study.

2.3. The Research Gap in North Africa

While the global literature is rich, focused academic research on the macroeconomic impact of digitalization in North Africa remains limited and exhibits notable gaps. Existing work on the region tends to be qualitative, descriptive (Gelvanovska et al., 2014), or confined to single-country case studies (Emara & Katz, 2024; Katz & Emara, 2022). The few multi-country econometric studies present conflicting conclusions—some reporting a positive impact of ICT (Benazzouz & Sadok, 2024; Saba et al., 2024), while others, notably Bakari and Tiba (2020), find a significant *negative* effect of internet on growth for four North African economies. This contradiction underscores a critical methodological gap: a lack of comparative, multi-country analyses that formally account for unobserved heterogeneity,

test for non-linearities, and examine the conditional role of structural factors like urbanization. This study directly addresses these gaps by applying a fixed-effects panel model with quadratic and interaction terms to test for threshold and complementary effects specific to the North African context.

2.4. Positioning of the Present Study

Building on this theoretical and empirical foundation, the present study aims to resolve the contradictions in the North African literature and address its methodological gaps. Unlike prior studies that often assume a linear relationship or focus on single-country analyses, this research employs a fixed-effects panel model for five North African economies. It explicitly tests two core hypotheses derived from the literature: first, that the internet-growth relationship in the region is non-linear and follows a U-shaped pattern; second, that this relationship is positively conditioned by the level of urbanization. By testing for both threshold and complementary effects, this study moves beyond contested linear assumptions. It seeks to provide evidence-based insights into the specific structural conditions and critical mass required for a digital dividend to materialize in North Africa.

3.Methods

3.1. Data Source and DataCollection

This study employs a balanced panel dataset comprising annual observations for five North African economies—Algeria, Egypt, Libya, Morocco, and Tunisia—spanning the period from 2000 to 2023. The primary data source is the World Bank's World Development Indicators (WDI) database, which represents the most comprehensive and widely utilized collection of cross-country development statistics. The selected timeframe encompasses a critical period of digital transformation, beginning with the early diffusion of internet technologies at the turn of the millennium and extending through the rapid expansion of mobile broadband and digital services in recent years. This twenty-four-year window captures multiple business cycles, significant global economic events including the 2008 financial crisis, and region-specific developments such as the Arab Spring, offering a robust basis

for analyzing the evolving relationship between digital infrastructure and economic performance under varying conditions.

Given the geopolitical instability characterizing parts of the region, data quality and consistency presented specific challenges that required rigorous preprocessing. In particular, the economic data for Libya exhibited extreme volatility due to the conflict and subsequent political transitions, with GDP growth rates oscillating dramatically from -50.3% in 2011 to 86.8% in 2012. Such outliers, if left unaddressed, could severely bias the econometric estimation and distort the identification of regional trends. To mitigate this issue without reducing the sample size through listwise deletion, a winsorization technique was applied to the dependent variable. Specifically, the real GDP growth rate was capped at the 5th and 95th percentiles within the distribution. This statistical adjustment preserves the continuity of the time series while reducing the influence of spurious extremes, thereby ensuring that the estimated coefficients reflect structural economic relationships rather than transient shocks.

3.2. Variable Definitions and Measurements

The empirical analysis examines the relationship between digital infrastructure development and economic growth, incorporating key control variables to account for other fundamental determinants of economic performance. To ensure clarity and conciseness in model specification and discussion, precise definitions for all variables are established.

The dependent variable is the annual growth rate of real GDP, denoted as *GDPgrW*. As previously noted, this variable has been winsorized to limit the impact of outliers. It serves as the primary metric for economic performance, capturing the year-on-year expansion of economic output adjusted for inflation.

The primary independent variable of interest is Internet Penetration (*Internet*), measured as the percentage of the population with access to the global internet. While various indicators such as fixed broadband subscriptions or secure internet servers exist, internet penetration remains the most consistent and widely available proxy for general digital

adoption in developing contexts. Preliminary diagnostic tests, specifically the Variance Inflation Factor (VIF) analysis, revealed severe multicollinearity when internet penetration was included alongside mobile cellular subscriptions and fixed broadband indicators. Consequently, to maintain model parsimony and statistical validity, internet penetration is retained as the principal explanatory variable for digital infrastructure, as it broadly captures the extent of connectivity within the society.

To isolate the effect of digital infrastructure, the model includes two critical control variables. The first is the Urbanization Rate (*Urban*), measured as the share of the population living in urban areas. Urbanization is included to control for agglomeration economies, as the concentration of economic activity in cities is historically associated with higher productivity and growth. Furthermore, urbanization often acts as a prerequisite for efficient digital infrastructure deployment, making it a vital confounder to address. The second control variable is GDP per Capita (*GDPpc*), measured in constant 2015 US dollars. Including the initial level of income controls for conditional convergence effects, based on the neoclassical growth theory prediction that economies with lower initial capital stocks tend to grow faster than mature economies. Table 1 provides a comprehensive summary of all variables utilized in the analysis, including their abbreviations, definitions, measurements, and sources.

Table(01): Variable Definitions and Measurements

Variable Name	Abbreviation	Definition	Measurement
GDP Growth (Winsorized)	<i>GDPgrW</i>	Annual real GDP growth rate with extreme values adjusted	Percentage change, winsorized at country-level 5th/95th percentiles
Internet Penetration	<i>Internet</i>	Proportion of population with access to the internet	Percentage of population
Urbanization Rate	<i>Urban</i>	Share of population living in urban areas	Percentage of total population
GDP per Capita	<i>GDPpc</i>	Economic output per person, controlling for price changes	Constant 2015 US Dollars
Fixed Broadband	<i>FixBB</i>	Subscriptions to high-speed fixed-line internet services	Per 100 inhabitants
Mobile Subscriptions	<i>Mobile</i>	Subscriptions to mobile cellular telephone services	Per 100 inhabitants
Internet Squared	<i>Internet²</i>	Quadratic term to capture non-linear effects	Square of the <i>Internet</i> variable
Interaction Term	<i>Int×Urb</i>	Interactive effect between digital and urban development	Product of <i>Internet</i> and <i>Urban</i> variables

3.3. Econometric Models Employed in the Study

The core of the analysis employs a panel data approach to estimate the impact of digital infrastructure on economic growth. Given the specific nature of the sample, which consists of five distinct countries with diverse historical, institutional, and geographical characteristics, the assumption that the error term is uncorrelated with the regressors is likely violated. Unobserved heterogeneity, such as the quality of governance, cultural attitudes toward technology, or geographic accessibility, could simultaneously influence both internet adoption and economic growth.

To address this endogeneity arising from omitted variable bias, the Hausman specification test was conducted to choose between Fixed Effects (FE) and Random Effects (RE) models. The test results strongly rejected the null hypothesis that the unique errors are uncorrelated with the regressors. Therefore, the Fixed Effects estimator is utilized for all regression specifications. By including country-specific intercepts, the FE model controls for all time-invariant country characteristics, focusing the estimation on within-country variations over time.

3.3.1. Baseline Linear Model

The initial investigation begins with a standard linear growth model to test the direct relationship between internet penetration and economic expansion. This baseline specification assumes a constant marginal effect of digital adoption. The estimating equation is specified as follows:

$$GDPgrW_{it} = \alpha_i + \beta_1 Internet_{it} + \beta_2 Urban_{it} + \beta_3 GDPpc_{it} + \varepsilon_{it} \quad (1)$$

In this equation, i denotes the country and t denotes the year. The α_i represents the country-specific fixed effects, and ε_{it} is the idiosyncratic error term. The coefficient β_1 estimates the percentage point change in GDP growth associated with a one percentage point increase in internet penetration, holding urbanization and income levels constant.

3.3.2. Testing for Non-Linearity: The Quadratic Model

Theoretical literature on the “network effect” suggests that the economic impact of digital technologies may not be linear. Metcalfe’s Law posits that the value of a network is proportional to the square of the number of connected users, implying that digital infrastructure might only contribute significantly to growth after reaching a critical mass of adoption. This specification is motivated by empirical findings of non-linear ICT-growth relationships in other developing regions (e.g., Kouam & Asongu, 2023; Abdulqadir & Asongu, 2022). To empirically test this hypothesis, a quadratic term for internet penetration is introduced into the model (2):

$$GDPgrW_{it} = \alpha_i + \beta_1 Internet_{it} + \beta_2 Internet_{it}^2 + \beta_3 Urban_{it} + \beta_4 GDPpc_{it} + \varepsilon_{it} \quad (2)$$

Here, the statistical significance and sign of β_2 are of central interest. A positive and significant β_2 combined with a

negative β_1 would indicate a U-shaped relationship, suggesting the existence of a threshold level of internet penetration below which the growth effects are negligible or negative, and above which the digital dividend materializes.

3.3.3. The Interaction Mechanism

Beyond the direct effects, the impact of digital technologies is likely contingent on complementary structural factors. Urban areas, with their density of skilled labor and service-oriented businesses, may be better positioned to leverage digital connectivity for productivity gains compared to rural areas. To examine this potential synergy, an interaction term between internet penetration and urbanization is added to the model (3):

$$GDPgrW_{it} = \alpha_i + \beta_1 Internet_{it} + \beta_2 (Internet_{it} \times Urban_{it}) + \beta_3 Urban_{it} + \beta_4 GDPpc_{it} + \varepsilon_{it} \quad (3)$$

A positive coefficient for the interaction term β_2 would imply that the marginal effect of internet penetration on growth increases as the level of urbanization rises, highlighting the complementary role of physical and digital agglomeration. This approach follows recent studies examining the synergy between digital infrastructure and urbanization (e.g., de Clercq et al., 2023; Hussain et al., 2024).

3.4. Diagnostic Tests and Robustness

To ensure the reliability of the statistical inference, a series of diagnostic tests were performed on the residuals of the baseline models. The Breusch-Pagan test strongly rejected the null hypothesis of homoskedasticity, indicating that the variance of the error terms is not constant. Additionally, the Wooldridge test for serial correlation and the Pesaran CD test for cross-sectional dependence pointed to the presence of autocorrelation and spatial dependence within the panel.

In light of these diagnostic results, standard errors in all regression models are clustered at the country level. Cluster-robust standard errors provide valid inference even in the presence of heteroskedasticity and within-group serial correlation. Furthermore, robustness checks are conducted by re-estimating the models after excluding specific outliers and

time periods, such as the years of the Arab Spring, to verify that the identified relationships are structural rather than artifacts of transient geopolitical shocks.

3.5. Methodological Limitations

Although the study is designed to provide robust insights, several limitations inherent to the data and methodology must be acknowledged. Primarily, the analysis covers only five countries, which results in a relatively small cross-sectional sample size. Even though the panel length spans twenty-four years, this small-N context constrains statistical power and precludes the use of more complex econometric methods that typically require a larger number of independent units.

Furthermore, the variables utilized serve as imperfect proxies for the complex phenomena of digital development. Specifically, internet penetration measures access but fails to capture the intensity, quality, or productive application of that connectivity. Additionally, data availability constraints prevented the incorporation of other potentially critical factors, such as the quality of human capital, research and development expenditure, institutional quality, or regulatory environments, all of which likely influence how digital technologies translate into economic growth. Finally, while the Fixed Effects model effectively controls for time-invariant confounders, the possibility of reverse causality or omitted time-varying factors cannot be entirely ruled out. These limitations suggest that the results should be interpreted as identifying robust conditional correlations that inform the broader debate rather than establishing definitive causal relationships, thus delineating important avenues for future research as richer data becomes available for the region.

4. Results

4.1. Descriptive Statistics and Correlation Analysis

This chapter presents the empirical findings regarding the relationship between digital infrastructure and economic growth in North Africa. The analysis begins with an examination of the descriptive statistics for the key variables employed in the study, which are summarized in Table 2. The dataset comprises 120 observations across five North African economies over the

period 2000–2023, although the number of complete observations varies slightly by variable due to sporadic data unavailability.

The winsorized GDP growth rate (*GDPgrW*) exhibits a mean of 3.11% with a standard deviation of 6.64%, a dispersion that indicates substantial economic volatility within the region. This variability is particularly pronounced in the case of Libya, which experienced extreme growth fluctuations during periods of conflict and post-conflict recovery. Consequently, the application of winsorization was essential to preserve the structural integrity of the estimation. Internet penetration (*Internet*) displays a mean of 33.48% but is characterized by significant heterogeneity, evidenced by a standard deviation of 27.42%. The range extends from a minimum of 0.19% in the early years of the sample to maximum values approaching saturation in recent years, highlighting the rapid yet asynchronous digital transformation that has unfolded across these economies. Urbanization rates (*Urban*) average 64.39%, with Libya exhibiting exceptionally high urbanization figures due to its specific geographic and historical settlement patterns.

Economic output per person (*GDPpc*) displays considerable variation, with a mean of \$4,857 (constant 2015 USD) and a standard deviation of \$3,000, underscoring the deep economic diversity within the sample. Regarding specific ICT infrastructure, Fixed Broadband subscriptions (*FixBB*) remain relatively low on average at 3.81 per 100 people, although recent years have witnessed an upward trend. In contrast, Mobile subscriptions (*Mobile*) have achieved near-universal penetration in several contexts, with a mean of 85.12 subscriptions per 100 inhabitants.

Table (02): Descriptive Statistics

Variable	Mean	SD	Min	Max	N
GDPgrW	3.11	6.64	-7.52	17.94	115
Internet	33.48	27.42	0.19	96.54	115
Urban	64.39	14.81	42.73	90.32	120
GDPpc	4857	3000	1653	13582	115
FixBB	3.81	4.95	0.00	17.85	101
Mobile	85.12	41.24	0.28	172.73	118

Note: GDPgrW is winsorized GDP growth (%), Internet is internet penetration (% of population), Urban is urbanization rate (%), GDPpc is GDP per capita (constant 2015 USD), FixBB is fixed broadband subscriptions (per 100 people), Mobile is mobile subscriptions (per 100 people).

The correlation matrix presented in Table 3 offers preliminary insights into the bivariate relationships between these variables. Internet penetration shows a moderate positive correlation with GDP per capita (0.43), which suggests that wealthier nations in the region tend to possess higher levels of digital adoption. However, the raw correlation between internet penetration and GDP growth is weak (0.08) and statistically insignificant. This lack of a strong simple correlation provides initial evidence against a linear, unconditional relationship between digital expansion and economic growth. Furthermore, the high intercorrelations among the ICT variables, ranging from 0.61 to 0.85, indicate that these metrics capture overlapping dimensions of the digital economy, thereby justifying the primary focus on internet penetration to mitigate potential multicollinearity in the regression analysis.

Table (03): Correlation Matrix

	GDPgrW	Internet	Urban	GDPpc	FixBB	Mobile
GDPgrW	1.00					
Internet	0.08	1.00				
Urban	0.07	0.09	1.00			
GDPpc	0.12	0.43 ^{**}	0.67 ^{***}	1.00		
FixBB	0.05	0.85 ^{***}	0.06	0.31 [*]	1.00	
Mobile	0.13	0.61 ^{***}	-0.36 ^{**}	0.08	0.66 ^{***}	1.00

*Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

4.2. Results of Fixed Results

The core econometric analysis begins with the estimation of the baseline Fixed Effects models to test for a linear relationship between internet penetration and economic growth. Table 4 presents these results. Model 1 specifies the relationship with only internet penetration and urbanization as explanatory variables. The coefficient on internet penetration is negative (-0.016) and statistically indistinguishable from zero ($p=0.626$). This finding suggests that, absent other controls, there is no evidence of a direct linear growth effect from digital expansion in the region. Similarly, urbanization does not exhibit a significant effect in this sparse specification.

Model 2 introduces GDP per capita as a critical control for the initial level of development. The inclusion of this variable substantially improves the explanatory power of the model, as evidenced by the increase in the R-squared value to 0.237 and a highly significant F-statistic. The coefficient for GDP per capita is positive and significant (0.0033, $p<0.001$), indicating conditional convergence effects where the initial income level is a strong predictor of subsequent growth dynamics. In this specification, the coefficient for internet penetration becomes positive (0.044) but remains statistically insignificant ($p=0.165$). Urbanization, however, becomes significantly negative (-0.859), which may imply that once income levels are controlled for, rapid urbanization in the region could be associated with congestion costs or structural inefficiencies that dampen growth.

Diagnostic tests conducted on the residuals of these models revealed the presence of heteroskedasticity, serial correlation, and cross-sectional dependence. Consequently, all reported standard errors are robust and clustered at the country level to ensure valid statistical inference. The persistent insignificance of the internet variable in the linear specifications challenges the simplistic narrative of an automatic digital dividend and points toward the necessity of exploring more complex, non-linear functional forms.

Table(04): Fixed Effects Regression Results

	Model 1	Model 2	Model 3	Model 4
Dependent Variable	Basic	+GDPpc	Quadratic	Interaction
Internet	-0.016(0.033)	0.044(0.031)	-0.155 [*] (0.093)	-0.530 ^{***} (0.113)
Internet ²			0.0023 ^{**} (0.0010)	
Urban	-0.084(0.346)	-0.859 ^{**} (0.334)	-0.679 ^{**} (0.337)	-1.442 ^{***} (0.320)
GDPpc		0.0033 ^{***} (0.0006)	0.0035 ^{***} (0.0006)	0.0056 ^{***} (0.0007)
Int × Urban				0.0090 ^{***} (0.0017)
Observations	115	115	115	115
R ² (within)	0.008	0.237	0.272	0.393
F-statistic	0.45	11.06 ^{***}	9.90 ^{***}	17.14 ^{***}

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All models include country fixed effects.

4.3. Non-Linear and Interactive Relationships

The absence of a linear effect suggests that the relationship between digital infrastructure and economic performance may be contingent on reaching a critical mass of adoption. Model 3 tests this hypothesis by introducing a quadratic term for internet penetration. The results provide compelling evidence of a U-shaped relationship. The coefficient for the linear term is negative and significant at the 10% level (-0.155), while the quadratic term is positive and significant at the 5% level (0.0023). This pattern indicates that at low levels of digital adoption, further investment in internet infrastructure may initially act as a drag on growth, possibly due to the high fixed costs of deployment or the displacement of traditional industries. However, once adoption surpasses a critical threshold, the network effects dominate, and the contribution to growth becomes positive.

Based on the estimated coefficients, the turning point of this U-shaped curve is calculated at approximately 33.7%

internet penetration $-\frac{\beta_1}{2\beta_2}$. This threshold holds significant policy implications for the region. In the early years of the sample, all five countries fell below this level, which explains the lack of a positive effect in the linear model. It is only in the later years, as countries like Morocco and Tunisia crossed this threshold, that the growth-enhancing potential of the digital economy began to materialize.

Furthermore, Model 4 explores the conditional nature of this relationship by interacting internet penetration with the urbanization rate. The results reveal a highly significant positive interaction term (0.0090, $p < 0.001$). This finding suggests that the economic returns to digital infrastructure are amplified in more urbanized environments. While the main effect of internet penetration appears negative (-0.530) in this specification, this must be interpreted conditionally. The positive interaction implies that urban centers, with their density of skilled labor and complementary services, provide the necessary ecosystem for digital technologies to translate into productivity gains. For a country with an average urbanization rate of 64.4%, the net marginal effect of internet penetration becomes positive, confirming the synergistic relationship between agglomeration and digitalization.

4.4. Robustness Checks and Additional Analyses

To verify the validity of these findings, a series of robustness checks were conducted, the results of which are summarized in Table 5. Model 5 re-estimates the baseline relationship after excluding Libya from the sample. Given the extreme volatility observed in the Libyan data, this check ensures that the results are not driven by a single outlier. The coefficient on internet penetration remains statistically insignificant (-0.011) in the linear specification, confirming that the absence of a simple linear relationship is a general feature of the region rather than an artifact of Libyan instability.

Table(05): Robustness Checks

	Model 5	Model 6	Model 7
Check Type	Exclude Libya	Exclude Crises	Post-2005
Internet	-0.011(0.011)	0.025 (0.031)	0.038 (0.038)
Urban	-0.118(0.102)	-0.643* (0.336)	-0.912** (0.365)
GDPpc		0.0025*** (0.0006)	0.0031*** (0.0007)
Observations	96	110	90
R² (within)	0.118	0.155	0.204

*Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model 6 excludes years 2008-2009 and 2011-2013. Model 7 uses data from 2005 onward.*

Model 6 addresses potential temporal anomalies by excluding the years associated with the global financial crisis (2008–2009) and the Arab Spring (2011–2013). Even after removing these periods of exceptional economic disruption, the coefficient on internet penetration remains statistically insignificant (0.025), while the control for GDP per capita retains its strong positive significance. This suggests that the identified patterns are structural and robust to major external shocks. Additionally, Model 7 restricts the sample to the post-2005 period, during which internet adoption became more substantial. The results are qualitatively similar to the full sample estimates, although the reduced sample size affects statistical power.

4.5. Summary of Key Findings

The empirical evidence presented in this section offers a nuanced perspective on the digital economy in North Africa that challenges conventional wisdom. Contrary to the expectation of an automatic “digital dividend,” the analysis finds no statistically significant linear relationship between internet penetration and economic growth across the full sample. Instead, the data supports a non-linear, U-shaped relationship, characterized by a critical threshold of approximately 33.7% penetration. Below this level, the growth effects of digital infrastructure are negligible or potentially negative, likely due to the initial costs of investment and adjustment.

Moreover, the positive impact of digital technologies appears to be strongly contingent on the level of urbanization. The significant interaction effect indicates that digital infrastructure complements urban agglomeration, yielding higher economic returns in cities where the necessary human capital and service networks are concentrated. These findings underscore that the path to a digital economy is not linear but requires achieving a critical mass of adoption and fostering complementary structural conditions.

5. Discussion

5.1 Interpretation of Key Findings

The empirical results establish that the relationship between internet penetration and economic growth in North Africa is not linear but contingent on two critical factors: a threshold level of adoption and the degree of urbanization. This complexity directly addresses the research question and challenges the assumption of a universal digital dividend.

The absence of a significant linear effect aligns with earlier literature on the “productivity paradox” in developing contexts. In the North African setting, this can be interpreted as evidence that the substantial investments in digital infrastructure during early stages of diffusion may not yield immediate macroeconomic returns. Potential explanations include high initial capital expenditures displacing other productive investments, a time lag required for businesses and individuals to adapt and innovate using new technologies, and the initially limited scope of the digital ecosystem necessary for widespread economic application.

Our identified threshold of 33.7% offers a region-specific benchmark. It lies between the very low threshold found for basic internet access in Sub-Saharan Africa (Abdulqadir & Asongu, 2022) and the higher prerequisite for fixed broadband linked to electrification (Kouam & Asongu, 2023). This intermediary position may reflect the composite nature of our ‘internet penetration’ variable and the specific stage of digital development in North Africa. It signifies a potential tipping point where network externalities begin to dominate initial costs, enabling a user base sufficient to support vibrant digital markets

and overcome the “third-level divide” (Van Deursen & Helsper, 2015).

The significant positive interaction between internet penetration and urbanization provides robust empirical support for the complementary assets theory. This finding confirms that urbanization, acting as a proxy for agglomeration economies and the concentration of complementary resources, critically amplifies digital returns (Dasgupta et al., 2001). It aligns with recent evidence of digital-urban synergy in other regions (Hussain et al., 2024). Urban centers in North Africa concentrate the essential ingredients for digital value creation. Consequently, digital technology acts as a general-purpose technology whose productivity impact is magnified within dense, networked urban environments. Conversely, in less urbanized areas, the absence of these complements may limit the translation of connectivity into measurable growth, potentially exacerbating spatial inequalities.

5.2 .Theoretical and Policy Implications

5.2.1. TheoreticalImplications

This study contributes to three strands of literature. First, it extends the digital divide discourse beyond simple access metrics, demonstrating that the economic consequences of access are conditional and non-linear. Second, it provides strong empirical support for the complementary assets framework in a regional context, highlighting urbanization as a critical structural complement to ICT. Third, it adds nuance to the technology-growth nexus by identifying a specific adoption threshold, thereby bridging macroeconomic analysis with theories of technology diffusion and network effects.

5.2.2. PolicyImplications

The findings suggest that a uniform digital expansion policy is insufficient. A phased, integrated strategy is warranted:

1. **Pre-Threshold Focus (Building Foundations):** For areas or sectors below the ~34% penetration threshold, policy should prioritize building the fundamental complements. This includes investing in digital literacy and skills training to build human capital, improving logistical and financial infrastructure to enable e-commerce, and

fostering a regulatory environment conducive to digital entrepreneurship. The goal is to lower the adoption and effective-use costs.

2. **Post-Threshold Focus (Leveraging Networks):** For contexts above the threshold, policy should shift towards stimulating demand and innovation. This can involve promoting digital platforms for SMEs, implementing “smart city” initiatives to boost urban efficiency, and encouraging digitalization in key sectors like agriculture, education, and government services (e-government) to maximize spillovers.
3. **Spatial Equity Considerations:** The urban bias in digital returns necessitates explicit policies to prevent a widening spatial manifestation of the third-level digital divide (Van Deursen & Helsper, 2015). Policy must address the deficit in complementary assets in rural and peri-urban areas. This requires targeted investment not only in digital infrastructure but also in parallel investments in digital literacy, logistical systems, and local entrepreneurial ecosystems. Programs to integrate these areas into urban-centric digital platforms, such as regional e-marketplaces, are also essential.

5.3. Limitations and Avenues for Future Research

This study has several limitations that also define paths for future inquiry. First, the small cross-sectional dimension (N=5) limits the generalizability of the precise threshold and confines the use of more advanced econometric techniques that require larger N. Future research could expand the sample to include other MENA or developing economies. Second, the reliance on internet penetration as a percentage of the population is a supply-side, quantity-based metric. It does not capture qualitative aspects like connection speed, affordability, or usage intensity, which are critical for measuring meaningful access. Third, while the model accounts for some key controls, other potential complementary factors—such as institutional quality, regulatory environment, and specific human capital levels—could be integrated into a more comprehensive framework.

Future research directions include: 1) employing dynamic panel models (System GMM) to better account for persistence in growth and potential endogeneity; 2) disaggregating ICT indicators (e.g., broadband vs. mobile, business vs. household use) to identify which facets of digitalization are most potent; 3) conducting sub-national or sectoral analyses to uncover heterogeneous effects within countries; and 4) incorporating direct measures of digital skills or innovation output to better trace the causal channels from infrastructure to growth.

6. Conclusion

This study investigated the impact of the digital divide on economic growth in North Africa, moving beyond simplistic linear assumptions. Through a fixed-effects panel analysis from 2000 to 2023, it reveals a complex, conditional relationship. The core conclusion is that the digital dividend in the region is not automatic but contingent. It is contingent first upon achieving a critical mass of adoption, approximated at 33.7% internet penetration, and second upon being strongly reinforced by the level of urbanization.

The finding of a U-shaped relationship indicates an initial phase where digital infrastructure investment may not yield positive growth returns, potentially explaining the negative or null findings in some prior studies of the region (e.g., Bakari & Tiba, 2020). This is followed by a second phase where network effects and complementarities catalyze positive impacts. The significant synergy with urbanization underscores that digital technology thrives within ecosystems rich in complementary assets and agglomeration economies.

These findings carry substantial implications. Theoretically, they reinforce the importance of non-linear models and complementary factors in understanding technology-driven growth. For policymakers in the region, they argue against one-size-fits-all digital strategies. Instead, they call for sequenced policies that first build the necessary human and physical complements, particularly in lagging regions, and then actively foster digital innovation and integration once a threshold of connectivity is achieved.

In summary, bridging the digital divide in North Africa requires more than just expanding infrastructure. It necessitates a parallel investment in the urban, educational, and institutional ecosystems that transform connectivity into productivity, ensuring that the digital transition contributes to inclusive and sustainable economic growth.

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