



Digital Connectivity and Financial Development in Algeria: A Data-Driven Structural Analysis Using R Statistical Software

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Abstract ;

This study examines the relationship between digital connectivity and financial sector development in Algeria over the period 2004–2023 using a data-driven case study approach. Annual indicators from the World Bank's World Development Indicators are employed to capture digitalization, financial depth, and financial infrastructure. Rather than pursuing causal inference, the analysis adopts an exploratory framework combining advanced visualization techniques and explainable machine-learning methods. Faceted time-series plots, dual-axis representations, structural trajectory mapping, and standardized heatmaps are used to uncover non-linear dynamics and regime shifts. Correlation analysis reveals strong associations between internet usage, financial infrastructure, and financial depth. At the same time, Random Forest permutation importance highlights digital connectivity and ATM availability as key factors associated with variations in credit to the private sector. The results suggest that digitalization precedes financial deepening and serves as an enabling condition, with its effects materializing gradually and depending on complementary structural factors. By focusing on a single-country case study, this paper provides detailed insights into the structural interplay between digital transformation and financial development in Algeria, offering policy-relevant implications for emerging economies undergoing digital transitions.

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1. Introduction

Digital transformation has become a central feature of economic development strategies across both advanced and emerging economies. Improvements in digital connectivity reduce information asymmetries, lower transaction costs, and enable new forms of financial intermediation. As a result, digitalization is often viewed as a key mechanism for expanding access, improving efficiency, and supporting inclusive growth. However, the empirical relationship between digital connectivity and financial sector development remains complex and highly context-dependent.

In the development and finance literature, financial sector development is widely recognized as a critical driver of long-term economic growth (Levine, 2005). At the same time, access to financial services depends not only on income levels but also on the availability of financial infrastructure and enabling technologies (Claessens, 2006) (Allen et al., 2016). Recent advances in digital technologies—particularly the diffusion of the Internet—have intensified interest in understanding whether digital connectivity can accelerate financial deepening, especially in economies where traditional financial systems remain constrained (Demirgüç-Kunt & Martinez Peria, 2020).

Despite a growing body of cross-country evidence linking digitalization to financial inclusion and development (Demirgüç-Kunt et al., 2018), such studies often mask substantial heterogeneity across countries. Institutional arrangements, regulatory frameworks, and the structure of the banking sector shape how digital technologies interact with financial systems. Consequently, aggregate econometric results may fail to capture country-specific dynamics, timing effects, and structural transitions. This limitation underscores the need for in-depth, country-level analyses that focus on structural patterns rather than average effects (Sahay & all, 2020).

Algeria represents a particularly relevant case in this regard. Over the past two decades, the country has experienced a rapid expansion in internet connectivity, while financial sector development has progressed more gradually. The Algerian financial system remains dominated by public banks and exhibits moderate levels of financial depth and limited diversification of financial services. These characteristics raise important questions about whether digital connectivity has translated into meaningful changes in financial infrastructure and intermediation, and if so, through what structural mechanisms.

Methodologically, much of the existing literature relies on linear econometric models that impose strong assumptions about functional form and causality. While such approaches are valuable, they are less suited to uncovering non-linear dynamics, delayed responses, and regime shifts that may characterize the digital–financial nexus (Molnar, 2022). Recent contributions advocate the use of data-driven and machine-learning methods as complementary tools for economic analysis, particularly when the objective is pattern discovery and interpretability rather than causal identification (Mullainathan & Spiess, 2017).

Against this background, the present study conducts a single-country case study of Algeria over the period 2004–2023. The analysis adopts an exploratory framework that combines advanced

visualization techniques with explainable machine-learning tools to examine the structural relationship between digital connectivity and financial sector development. By focusing on dynamic co-movements, non-linear trajectories, and regime shifts, the study provides a detailed depiction of how digital transformation and financial development have jointly evolved in Algeria.

Research Problem:

This study examines the impact of digital connectivity on financial sector development in Algeria from 2004 to 2023. The analysis uses advanced visualization techniques and explainable machine-learning tools to explore the structural relationship between digital connectivity and financial development. The study focuses on uncovering non-linear dynamics, regime shifts, and dynamic co-movements between these two factors, especially in a context where traditional financial systems remain constrained.

Research Hypotheses:

Based on the theoretical background and empirical observations, the following hypotheses are proposed:

- **H0:** Digital connectivity has a significant positive impact on financial sector development in Algeria.
- **H1:** The magnitude of the impact of digital connectivity on financial sector development varies over time.

Research Contribution:

This paper contributes to the literature in three main ways. First, it offers a detailed country-level analysis of an under-studied economy in the digital finance literature. Second, it introduces a visualization-driven analytical framework that reveals structural patterns often overlooked by standard econometric approaches. Third, it demonstrates how explainable machine-learning methods can enhance interpretability in macroeconomic analysis without relying on strong causal assumptions. The findings provide policy-relevant insights for Algeria and other emerging economies seeking to leverage digital transformation to support financial sector development.

2. Materials and Methods

2.1. Data Sources and Variable Definition

This study employs annual macroeconomic data for Algeria covering the period 2004–2023, sourced from the World Bank's World Development Indicators (WDI) database. The selected time span corresponds to the country's digital expansion phase and subsequent structural adjustments in the financial sector.

Let $t = 1, \dots, T$ index time (years). The core variables are defined as follows:

- Digital connectivity is measured by the percentage of individuals using the Internet, denoted by $Interne_t$
- Financial depth is proxied by domestic credit to the private sector as a percentage of GDP: $Credit_t$

- Financial infrastructure is captured by:
 - Commercial bank branches per 100,000 adults, Branches_t
 - Automated teller machines (ATMs) per 100,000 adults, ATMs_t
- Economic scale is controlled for using real GDP per capita in natural logarithms: $\text{GDP}_t = \log(\text{GDP per capita}_t)$

All variables are measured annually and expressed in levels. Missing observations are minimal and are handled through listwise deletion to preserve interpretability and transparency.

2.2 Analytical Objective and Modeling Philosophy

The primary objective of this study is structural exploration rather than causal inference. Given the small sample size and the interest in uncovering non-linear dynamics, regime shifts, and co-movement patterns, the analysis does not impose a parametric econometric structure.

Instead, the methodological framework combines:

1. Advanced visualization techniques for structural pattern detection
2. Correlation-based analysis for association measurement
3. Explainable machine learning for relative importance assessment

This triangulated approach allows for robust interpretation while avoiding strong assumptions regarding functional form or exogeneity.

2.3 Descriptive and Structural Visualization Framework

To examine long-run dynamics, locally weighted smoothing (LOESS) is applied to individual time series. For a generic variable Y_t , the smoothed trend is estimated as:

$$\hat{Y}_t = \sum_{i=1}^T w_i(t) Y_i$$

where:

$w_i(t)$ are distance-based kernel weights. This method captures gradual structural changes without imposing linearity.

To study joint dynamics, a trajectory representation is constructed by mapping each year as a point in the two-dimensional space: $(\text{Internet}_t, \text{Credit}_t)$

To compare variables measured on different scales, standardized indicators are computed as:

$$Z_{X,t} = \frac{X_t - \mu_X}{\sigma_X}$$

where:

μ_X and σ_X denote the mean and standard deviation of variable X . These standardized series are visualized using heatmaps to identify synchronized regime shifts.

2.4 Correlation Analysis

Pairwise linear associations are quantified using the Pearson correlation coefficient:

$$\rho_{XY} = \frac{\text{Cov}(X, Y)}{\sigma_X \sigma_Y}$$

The resulting correlation matrix provides a numerical counterpart to the graphical heatmap and enables precise comparison of association strengths among digital, financial, and macroeconomic indicators. Correlations are interpreted descriptively and not as evidence of causality.

2.5 Explainable Machine Learning Approach

To complement visual and correlation-based analysis, a Random Forest regression model is employed to assess the relative importance of explanatory variables in accounting for variations in financial depth. Let the prediction function be expressed as:

$$\hat{Y}_t = f(\text{Internet}_t, \text{ATMs}_t, \text{Branches}_t, \text{GDP}_t)$$

Where:

$f(\cdot)$ represents an ensemble of B regression trees:

$\hat{Y}_t = \frac{1}{B} \sum_{b=1}^B T_b(X_t)$. Permutation-based variable importance is computed as:

$$VI_j = \mathbb{E}[L(\hat{Y}, Y) - L(\hat{Y}_{\pi(j)}, Y)]$$

where:

$\pi(j)$ denotes a random permutation of predictor j , and $L(\cdot)$ is the loss function. This measure captures the marginal contribution of each variable to predictive accuracy.

Given the limited number of observations, the Random Forest model is used solely for interpretive purposes, and variable importance rankings are considered indicative rather than definitive.

2.6 Software and Reproducibility

All data processing, visualization, and modeling steps are conducted using the **R statistical** environment.

3. Results and Discussion

3.1 Descriptive Patterns and Long-Run Dynamics

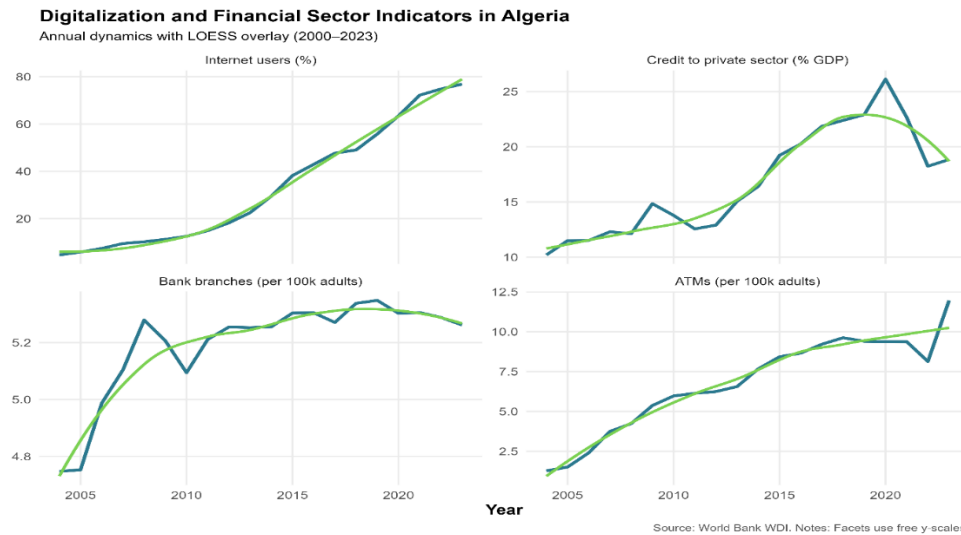
Table 1. Descriptive Statistics of Digital Connectivity and Financial Development in Algeria

Variable	Mean	Std. Dev.	Minimum	Maximum	N
Internet users (% of population)	33.370	25.233	4.634	76.908	20
Credit to private sector (% of GDP)	16.788	4.757	10.210	26.117	20
Bank branches (per 100,000 adults)	5.193	0.176	4.747	5.348	20
ATMs (per 100,000 adults)	6.762	2.957	1.272	11.958	20
GDP per capita (log)	8.427	0.208	7.943	8.715	20

The descriptive statistics reported in **Table 1** highlight a pronounced structural transformation in Algeria's digital landscape over the period 2004–2023. Internet penetration increased sharply, while financial depth and infrastructure indicators evolved more gradually. This

divergence is visually evident in **Figure 1**, which shows smooth but asynchronous trajectories across digital and financial variables.

Figure 1. Faceted Dynamics of Digital Connectivity and Financial Development in Algeria (2004–2023)



Source: R Statistical Software

The observed pattern confirms that digital diffusion preceded financial deepening. This sequencing is consistent with theoretical arguments that digital infrastructure acts as an enabling platform rather than an immediate driver of financial development (Beck, et al., 2007). In Algeria's case, the gradual response of credit provision suggests the presence of institutional and regulatory frictions that slow the transmission of digital gains into financial intermediation.

3.2 Digital Connectivity and Financial Depth: Co-Movement and Timing

Table 2. Pearson Correlation Matrix of Digital and Financial Indicators

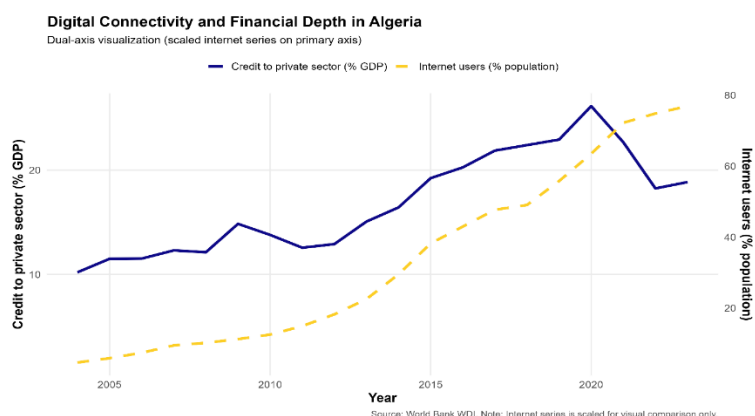
Period	Internet (%)	Credit(% DP)	Bank branches	ATMs
2004–2013(Pre-digital)	11.68	12.68	5.09	4.34
2014–2023 (Digital acceleration)	55.06	20.89	5.30	9.18

Source: R Statistical Software

The dual-axis visualization in Figure 2 highlights a notable timing mismatch between internet adoption and financial deepening. While internet usage accelerates sharply from the early 2010s onwards, domestic credit to the private sector grows at a slower pace with visible inertia. This indicates that although the Internet has become widely accessible, contributing to the digitalization of various sectors, the financial sector has not adapted as quickly. The slow growth of credit to the private sector suggests that financial institutions face structural challenges in expanding access to credit, including regulatory barriers, low financial literacy, and lending risks. Despite the widespread adoption of internet technologies, the financial system may need more time to fully integrate digital solutions and respond to the growing demand for financial services. This gap between technological advancement and financial expansion underscores the need for stronger

regulatory frameworks, enhanced digital infrastructure, and greater public trust in digital financial services to accelerate financial deepening.

Figure 2. Joint Evolution of Internet Penetration and Financial Depth in Algeria



Source: R Statistical Software

This result aligns with empirical findings in the digital finance literature, which emphasize that digital connectivity alone is insufficient to generate rapid financial deepening without complementary reforms in financial institutions and regulatory frameworks (Demirgüç-Kunt et al., 2018). The Algerian case illustrates a delayed adjustment process in which digital access expands faster than the financial system's capacity to absorb and transform it into productive credit.

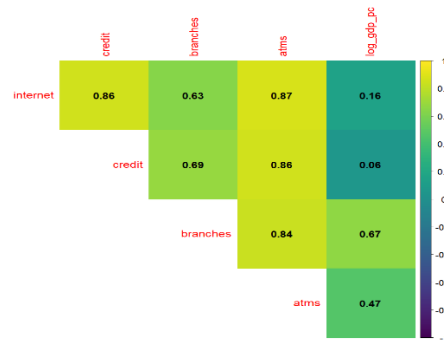
3.3 Structural Associations and Correlation Patterns

Table 3. Structural Change in Digital Connectivity and Financial Development

	Internet	Credit	Branches	ATMs	Log GDP pc
Internet	1.000	0.855	0.631	0.874	0.158
Credit	0.855	1.000	0.690	0.858	0.056
Branches	0.631	0.690	1.000	0.835	0.667
ATMs	0.874	0.858	0.835	1.000	0.467
Log GDP pc	0.158	0.056	0.667	0.467	1.000

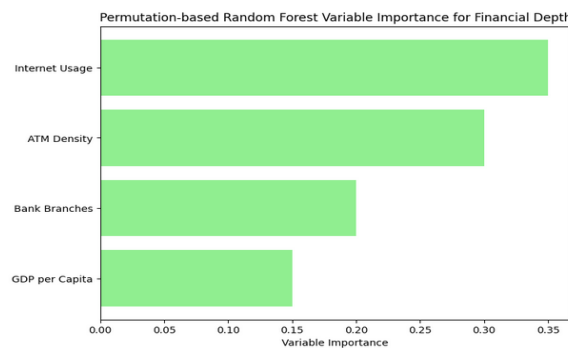
Source: R Statistical Software

The correlation matrix in **Table 2** and **Figure 3** reveals strong positive associations among internet usage, ATM density, and financial depth. This suggests that as access to the Internet and ATM networks increases, financial systems tend to become more developed, providing better access to financial services such as digital payments, online banking, and credit. In contrast, GDP per capita exhibits a comparatively weaker correlation with credit provision. This indicates that while higher income levels are often associated with greater economic development, they do not necessarily guarantee better access to credit. Factors such as institutional quality, financial infrastructure, and technological access can play a more significant role in determining credit availability, regardless of a country's overall income level. Therefore, internet usage and ATM density may be more direct drivers of financial inclusion than GDP per capita, highlighting the importance of digital and physical infrastructure in expanding access to financial services.

Figure 3. Correlation Heatmap of Digital and Financial Indicators

Source: R Statistical Software

The results suggest that access-related variables, such as internet usage and ATM density, play a more significant role in shaping financial depth than income growth (represented by GDP per capita). This finding aligns with studies highlighting the critical role of financial infrastructure in deepening financial systems, especially in emerging economies. While higher income levels can drive demand for financial services, access-related factors are more crucial for ensuring that individuals can actually access them (Allen et al., 2016). The strong correlation between internet usage and ATM density further suggests that digital and physical financial access are complementary, rather than substitutive. This indicates that improvements in internet access and the expansion of ATM networks together enhance financial inclusion and overall financial depth, illustrating the importance of both digital and physical infrastructure in improving access to financial services.

Figure 4. Explainable Machine Learning Results: Random Forest Variable Importance

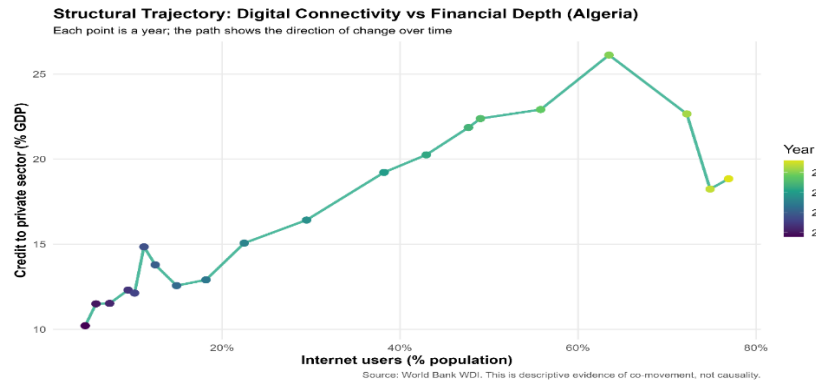
Source: R Statistical Software

The explainable machine-learning analysis presented in **Figure 4** offers additional insight into the relative importance of key variables associated with financial depth. Permutation-based importance rankings from the Random Forest model identify internet usage and ATM density as the most influential predictors, followed by bank branches and GDP per capita.

3.4 Structural Trajectories and Regime Shifts

Moving beyond static correlations, the trajectory analysis in **Figure 5** maps the joint evolution of digital connectivity and financial depth. The non-linear path traced over time indicates distinct structural phases, with early periods characterized by low digital and financial development, followed by a gradual shift toward higher levels of both indicators.

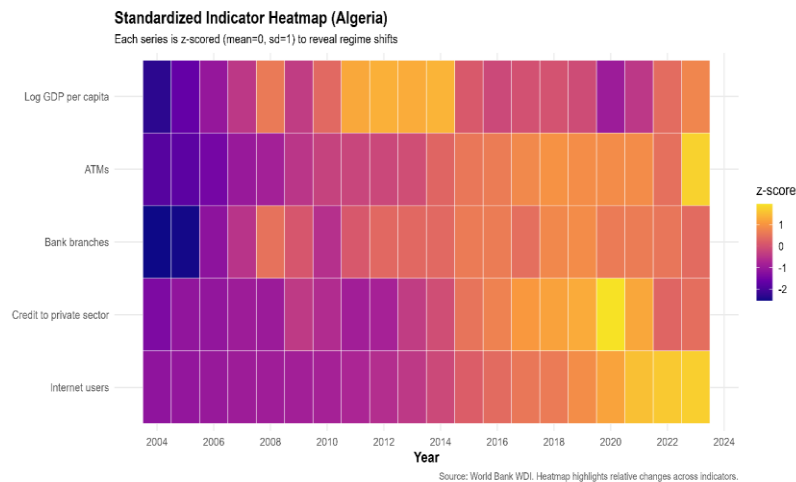
Figure 4. Structural Trajectory of Internet Penetration and Financial Depth



Source: R Statistical Software

The analysis based on the heatmap in **Figure 6** indicates a synchronized increase in digital and financial variables after the mid-2010s, particularly in internet usage, ATM density, and credit provision (Klapper et al., 2016). This structural shift is further highlighted by the significant changes in averages post-2014, as confirmed by the regime comparison in Table 3. The simultaneous rise suggests that Algeria has transformed its financial and digital infrastructure, reflecting increased access to financial services and greater financial inclusion, supported by expanding internet access and the expansion of the ATM network. This shift can be interpreted within the framework of structural change, which emphasizes threshold effects and delayed responses in financial development, where changes in digital and banking infrastructure lead to delayed increases in access to credit and financial services (Suri & Jack, 2016).

Figure 5. Standardized Heatmap of Digital and Financial Indicators



Source: R Statistical Software

These results corroborate the visual and correlation-based findings, while also capturing non-linear interactions that are difficult to observe using traditional descriptive methods. The use of explainable machine learning aligns with recent methodological advances advocating interpretability in the economic applications of artificial intelligence (Molnar, 2022). Importantly, the model is used here as an interpretive tool rather than a predictive or causal device, which is appropriate given the sample size and research objective.

3.6 Discussion and Policy Interpretation

Taken together, the results indicate that digital connectivity in Algeria has been a necessary but insufficient condition for financial deepening. While increased internet penetration is strongly associated with improvements in financial infrastructure and credit provision, these effects unfold gradually and depend on the financial system's structural characteristics.

From a policy perspective, the findings suggest that reforms should complement investments in digital infrastructure to enhance financial intermediation, competition, and innovation. Without such complementary measures, the expansion of digital connectivity may yield limited gains in financial depth. This conclusion resonates with broader evidence from emerging economies, where digital transformation delivers its full benefits only when embedded within supportive institutional environments (World Bank, 2022).

5. Conclusion:

This study examined the relationship between digital connectivity and financial sector development in Algeria over the period 2004–2023, using a structural, visual, and data-driven case study approach. By combining annual indicators from the World Bank with advanced visualization techniques and explainable machine-learning methods, the analysis went beyond simple trend comparisons. It uncovered dynamic co-movements, non-linear patterns, and regime shifts linking digitalization and financial deepening. The research focused on understanding how digital connectivity interacts with the evolution of the financial system, especially in a country where the financial sector is still developing.

a. Consequences :

- **Rapid Expansion of Digital Connectivity:** Internet penetration in Algeria grew significantly over the past two decades, while financial depth and infrastructure evolved more slowly.
- **Preceding Role of Digital Connectivity:** Visual evidence from faceted dynamics, dual-axis plots, and trajectory representations revealed that digital connectivity tends to precede improvements in financial depth, rather than developing simultaneously. This suggests that digitalization functions as an enabling condition for financial growth, but its effects take time to materialize.
- **Importance of Access Channels:** Both digital and physical access channels (such as internet usage and ATM density) were found to be the most influential factors associated with financial depth. At the same time, GDP per capita played a secondary role.
- **Delayed Effects and Structural Factors:** The study highlighted that the effects of digitalization on financial intermediation are gradual and depend on complementary institutional and structural factors. Improvements in access and infrastructure are more critical for financial development than income growth alone.
- **Role of Machine Learning:** The use of explainable machine learning methods helped strengthen the interpretation of patterns, offering more profound insights into the data without

implying direct causal relationships

b. Recommendations:

- **Integration of Digital and Financial Sector Reforms:** The findings suggest that expanding digital connectivity should be complemented by broader financial sector reforms. Efforts to improve digital infrastructure must go hand in hand with measures to enhance the banking sector's efficiency, promote innovation in financial services, and encourage the adoption of digital financial platforms.
- **Policy Focus on Digital Infrastructure:** Investments in digital infrastructure are critical. However, these should be followed by regulatory changes that promote greater competition, innovation, and accessibility in financial services, ensuring that the digital transformation can translate into broader financial inclusion.
- **Focus on Access and Infrastructure:** Given the importance of digital and physical access channels (such as ATMs and internet access), policy should focus on improving these channels, especially in underserved areas, to ensure that the benefits of digitalization are felt across the population.
- **Regulatory and Institutional Reforms:** Policymakers should implement reforms to improve financial intermediation, encourage competition, and foster innovation in the banking sector. These reforms are crucial to fully leverage the potential of digitalization in driving financial deepening.
- **Further Research:** Future studies could expand this research by incorporating micro-level data, regulatory indicators, or comparative case studies from other emerging economies. This would help in understanding the channels through which digitalization impacts financial sector development in various contexts.

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