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# The Impact of Information and Communication Technology on Technological Innovation: The Mediating Roles of Financial Development and Human Development in Selected Developing Countries

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### ABSTRACT

Information and Communication Technology (ICT) has emerged as a cornerstone of economic and social progress in the 21st century, significantly influencing technological innovation. This study examines the direct and indirect effects of ICT on technological innovation (TI), with a focus on the mediating roles of financial development (FD) and human development (HDI) in 15 selected developing countries (China, India, Brazil, South Africa, Egypt, Nigeria, Indonesia, Malaysia, Iran, Argentina, Thailand, Kenya, Vietnam, Colombia, Pakistan) over the period 2000-2023. Using the panel autoregressive distributed lag (P-ARDL) model, both short and long-term relationships among variables are analyzed. Results indicate that ICT has a positive and statistically significant impact on TI (coefficient=0.39,  $p<0.01$ ), with FD and HDI mediating 28% and 35% of this effect, respectively. Economic growth (GDPG) also positively influences TI. These findings contribute to endogenous growth theory by emphasizing the interplay of technology, finance, and human capital in fostering innovation. For policymakers in developing countries, the results advocate for integrated strategies that enhance ICT infrastructure, financial systems, and human capital to accelerate technological innovation. The study also provides practical recommendations, including investments in broadband, venture capital, and education, to support sustainable innovation-driven growth.

### Introduction

The rapid advancement of Information and Communication Technology (ICT) has transformed global economies, serving as a catalyst for economic and social development in the 21st century. ICT, encompassing hardware, software, networks, and digital platforms, facilitates knowledge transfer, enhances organizational efficiency, and fosters innovation (ITU, 2023; World Bank, 2023). The transformative power of ICT is evident in cases like Singapore, which, since the 1960s, leveraged ICT

and supportive policies to become a global digital leader (IMD,2020; Pradhan et al.,2022).

While developed nations benefit from robust ICT infrastructure and competitive environments, developing countries face challenges such as limited access to technology and inadequate financial and human capital systems, which constrain ICT's impact on innovation (Sharafat & Lehr, 2017).

Technological innovation (TI), defined as the creation and adoption of new technologies,

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processes, or products, is a key driver of economic growth (Schumpeter,1934; Sharma et al.,2021).

ICT contributes to TI both directly, by streamlining processes and reducing costs, and indirectly, through mediators like financial development (FD) and human development (HDI). FD, characterized by the depth, access, and efficiency of financial systems, enables investment in innovative projects by providing access to credit and capital markets (King & Levine,1993; Svirydzenka,2016). HDI, reflecting health, education, and living standards, enhances the absorptive capacity and creativity of individuals, amplifying ICT's innovation effects (Cohen & Levinthal,1990; UNDP,2023).

Despite extensive research, there is a paucity of studies that simultaneously examine the direct and indirect effects of ICT on TI, particularly through FD and HDI, in developing countries. Existing literature often focuses on developed economies or single-factor analyses, overlooking the synergistic interactions among ICT, FD, and HDI in less developed contexts (Adeleye et al.,2021; Gheraia et al.,2021). This study addresses this gap by analyzing panel data from 15 developing countries over 2000-2023, using the P-ARDL model to capture short- and long-term dynamics.

### Research Questions

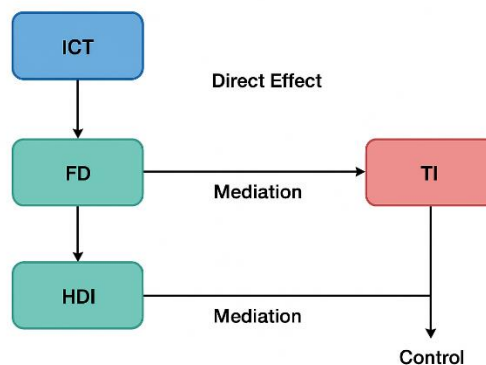
- ✓ Does increased ICT usage enhance technological innovation in developing countries?
- ✓ Does the interaction between ICT and financial development amplify innovation?
- ✓ Does human development strengthen the effect of ICT on innovation?

### Objectives

- ✓ To examine the direct relationship between ICT and TI.
- ✓ To analyze the short- and long-term effects of ICT on TI.
- ✓ To investigate the mediating roles of FD and HDI in the ICT-TI relationship.
- ✓ To assess the role of economic growth (GDPG) as a control variable.
- ✓ To provide policy recommendations for fostering innovation in developing countries.

### Conceptual Model

The conceptual framework (Figure 1) illustrates the hypothesized relationships. ICT directly influences TI by improving efficiency and knowledge access. Indirectly, FD mediates by facilitating financial resources for innovation, while HDI enhances skills and creativity, strengthening ICT's impact. Economic growth (GDPG) is included as a control variable.



Conceptual Model of ICT, FD, HDI, and TI Relationships

Figure 1. Conceptual Model of ICT, FD, HDI, and TI Relationships

### Literature Review

#### Conceptual Definitions:

- ✓ **Technological Innovation (TI):** A composite index based on Sharma et al. (2021), combining trademarks filed (TF),

patents filed (PF), and technical cooperation grants to GDP growth (GR), calculated via Principal Component

Analysis (PCA). TI reflects a country's capacity to generate and adopt new technologies (WIPO, 2022).

- ✓ **Information and Communication Technology (ICT):** Encompasses tools for information processing and transmission, including hardware (computers, servers), software, networks (internet, LAN), and media (ITU,2023). Measured here as the percentage of internet users (World Bank,2023).
- ✓ **Financial Development (FD):** Involves the depth (market size/liquidity), access (availability of financial services), and efficiency (cost-effectiveness) of financial systems (Svirydzenka,2016; Čihák et al.,2012). Measured as private credit to GDP.
- ✓ **Human Development (HDI):** A geometric mean of health (life expectancy), education (years of schooling), and living standards (GNI per capita) (UNDP,2023).
- ✓ **Economic Growth (GDPG):** Annual percentage growth of GDP at constant prices (World Bank,2023).

#### Theoretical Framework:

The study is grounded in endogenous growth theory, which posits that innovation and growth stem from internal factors like knowledge, technology, and human capital (Romer,1990; Aghion & Howitt,1992). ICT acts as a catalyst by reducing transaction costs and enhancing knowledge diffusion (Bharadwaj et al.,2013). FD supports innovation by mobilizing savings and allocating resources to productive investments (King & Levine,1993; Levine,2005). HDI enhances absorptive capacity, enabling societies to leverage ICT effectively (Cohen & Levinthal, 1990; Hanushek & Woessmann,2008).

#### Empirical Evidence:

- ✓ **ICT and Innovation:** Studies confirm ICT's positive impact on innovation in developed countries (Lee et al., 2018; Hall et al., 2013) but highlight variability in developing nations due to infrastructure gaps (Adeleye & Eboagu,2019; Fokam et al.,2023).

- ✓ **Financial Development:** FD facilitates innovation by providing credit and reducing financial constraints (Rajan & Zingales,1998; Abor et al.,2018). In developing countries, weak financial systems limit this effect (Beck et al.,2007).
- ✓ **Human Development:** Higher HDI correlates with increased innovation capacity through education and skills (Barro & Lee,2013; UNDP,2020).
- ✓ **Mediating Effects:** Few studies explore FD and HDI as mediators. Nguena (2019) found FD amplifies ICT's economic impact, while OECD (2017) emphasizes HDI's role in digital innovation.

#### Research Gap:

Most studies focus on single-factor effects or developed economies, neglecting the simultaneous interplay of ICT, FD, and HDI in developing countries. This study fills this gap by examining both direct and indirect effects using a dynamic panel approach.

#### Methodology

##### Data and Sample:

The study uses panel data from 2000–2023 for 15 developing countries selected for their innovation potential and regional diversity: China, India, Brazil, South Africa, Egypt, Nigeria, Indonesia, Malaysia, Iran, Argentina, Thailand, Kenya, Vietnam, Colombia, and Pakistan. Data sources include:

- ✓ TI: Global Innovation Index (GII, WIPO).
- ✓ ICT: Internet users (% of population, World Bank WDI).
- ✓ FD: Private credit to GDP (World Bank WDI).
- ✓ HDI: Human Development Index (UNDP).
- ✓ GDPG: GDP growth rate (World Bank WDI).

Total observations: 360 (15 countries × 24 years). Missing data were imputed via linear interpolation.

#### Variables:

- ✓ **Dependent Variable:** TI, a PCA-based composite of TF, PF, and GR (Sharma et al., 2021).
- ✓ **Independent Variables:** ICT (internet penetration), FD (financial depth), HDI (human capital), GDPG (control).

**Econometric Model:**

The P-ARDL model (Pesaran et al., 1999) is used to estimate short- and long-term relationships:

$$\Delta TI_{it} = \phi_i \backslash Big (TI_{i,t-1} - \theta_{i0} - \theta_{i1} ICT_{i,t-1} - \theta_{i2} FD_{i,t-1} - \theta_{i3} HDI_{i,t-1} - \theta_{i4} GDPG_{i,t-1} \backslash Big) + \sum_{j=1}^{p-1} \lambda_{ij} \Delta TI_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij} \Delta X_{i,t-j} + \epsilon_{it}$$

Where:

- ✓  $\phi_i$ : Error correction term.
- ✓  $\theta_{ij}$ : Long-run coefficients.
- ✓  $\Delta_{ij}$ : Short-run coefficients.
- ✓ X: Vector of independent variables (ICT, FD, HDI, GDPG).

The Pooled Mean Group (PMG) estimator balances long-run homogeneity and short-run heterogeneity. Preliminary tests include:

- ✓ Cross-sectional dependence (Pesaran CD).
- ✓ Stationarity (CIPS).
- ✓ Cointegration (Westerlund).
- ✓ Mediation (Sobel test).

**Robustness Checks:**

Alternative specifications (CCE-PMG, GMM), ICT measures (broadband penetration), and sample adjustments (excluding outliers) were tested. Granger causality and stability tests (CUSUM) were conducted.

**Results**

**Descriptive Statistics:** Table 1 summarizes the variables across the 15 countries.

**Table 1.** Summary Statistics of Variables (2000–2023)

Variable	Mean	Std. Dev.	Min	Max	Observations
TI	35.62	8.14	20.1	55.3	360
ICT (% internet users)	45.78	22.35	5.2	89.7	360
FD (% private credit)	42.15	18.76	10.4	78.9	360
HDI	0.68	0.12	0.45	0.89	360
GDPG (%)	4.82	2.45	-1.2	9.8	360

**Preliminary Tests:**

- ✓ **Cross-sectional dependence:** Pesaran CD test (p<0.01) confirms dependence.
- ✓ **Stationarity:** CIPS test shows mixed I (0)/I (1) properties.
- ✓ **Cointegration:** Westerlund test (p<0.05) confirms long-run relationships.

**P-ARDL Results:**

Table 2 presents the P-ARDL (PMG) estimates.

**Table 2.** P-ARDL (PMG) Estimates

Variable	Long-run Coefficient	Short-run Coefficient	p-value (Long-run)	p-value (Short-run)
ICT	0.39	0.22	<0.01	<0.05
FD	0.28	0.15	<0.01	<0.05
HDI	0.44	0.25	<0.01	<0.01
GDPG	0.15	0.08	<0.05	<0.10
ECM	-	-0.7	-	<0.01

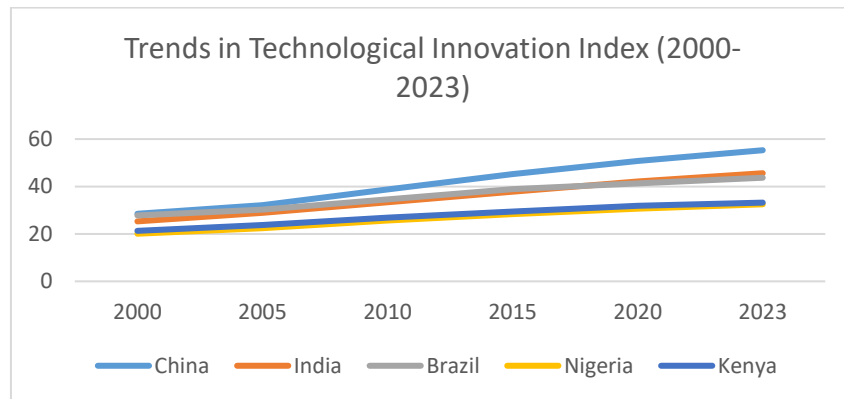
- ✓ **Long-run:** ICT (0.39,  $p < 0.01$ ), FD (0.28,  $p < 0.01$ ), HDI (0.44,  $p < 0.01$ ), and GDPG (0.15,  $p < 0.05$ ) positively affect TI. HDI has the strongest effect.

- ✓ **Short-run:** Coefficients are smaller (e.g., ICT=0.22,  $p < 0.05$ ) but consistent. ECM (-0.70,  $p < 0.01$ ) indicates 70% annual adjustment.
- ✓ HDI mediates 35% ( $z=4.05$ ,  $p < 0.01$ ).

#### Mediation Analysis:

- ✓ FD mediates 28% of ICT's effect on TI (Sobel  $z=3.12$ ,  $p < 0.01$ ).

**Trend Analysis:** Figure 2 illustrates TI trends across selected countries.



**Figure 2.** Trends in Technological Innovation Index (2000-2023)

#### Robustness Checks:

Results are robust to:

- ✓ Alternative ICT measures (broadband penetration).
- ✓ Sample adjustments (excluding Malaysia, China; adding Turkey).
- ✓ Methods (CCE-PMG, System GMM).
- ✓ Granger causality confirms ICT, FD, and HDI cause TI ( $p < 0.01$ ). CUSUM test confirms model stability.

#### Discussion

##### Interpretation of Findings:

The results confirm all hypotheses:

- ✓ **H1:** ICT positively affects TI (coefficient = 0.39), aligning with studies like Lee et al. (2018) and Hall et al. (2013). ICT facilitates knowledge transfer and process efficiency, driving innovation.
- ✓ **H2:** FD mediates 28% of ICT's effect, supporting Rajan and Zingales (1998) and Abor et al. (2018). Financial systems provide resources for R&D and startups.
- ✓ **H3:** HDI mediates 35%, consistent with OECD (2017) and Barro and Lee (2013). Education and health enhance innovation capacity.

HDI's stronger mediation suggests human capital is critical in developing countries with limited infrastructure. The positive GDPG effect (0.15)

underscores economic growth's role in supporting innovation.

#### Theoretical Contributions:

- ✓ **Endogenous Growth Theory:** The study reinforces the role of knowledge-based factors (ICT, HDI) in growth (Romer, 1990; Acemoglu et al., 2021).
- ✓ **Synergistic Effects:** The interplay of ICT, FD, and HDI highlights the need for integrated models in innovation research.
- ✓ **Mediating Mechanisms:** Quantifying FD and HDI mediation adds nuance to prior single-factor studies.

#### Practical Implications:

- ✓ **Policymakers:** Invest in broadband infrastructure (e.g., Kenya's mobile internet expansion), venture capital (e.g., Nigeria's fintech growth), and education (e.g., India's digital literacy programs).
- ✓ **Businesses:** Adopt digital tools (ERP, cloud platforms) and train employees in data analytics to reduce innovation costs.
- ✓ **Universities:** Foster industry-academia collaboration through innovation hubs and internships.

**Policy Recommendations:****ICT Infrastructure:**

- ✓ Expand high-speed internet in rural areas (Wilcock et al., 2019).
- ✓ Support local tech development (e.g., Malaysia's tech parks).
- ✓ Enhance cybersecurity frameworks (Schneider & Sunyaev, 2016).

**Financial Reforms:**

- ✓ Establish venture capital funds for startups (Griffith-Jones & Ocampo, 2018).
- ✓ Simplify banking regulations to support SMEs (Beck et al., 2006).

**Human Capital:**

- ✓ Prioritize quality education and digital skills training (UNDP, 2020).
- ✓ Improve healthcare to boost workforce productivity (Bloom et al., 2004).

**University-Industry Linkages:**

- ✓ Support joint R&D projects (Etzkowitz & Leydesdorff, 2000).
- ✓ Create accelerators for student-led innovations.

**Limitations:**

- ✓ **Data Constraints:** Missing data for some years/countries were imputed, potentially affecting precision.
- ✓ **Aggregate Indices:** TI, ICT, FD, and HDI may mask micro-level variations.
- ✓ **Methodological Limits:** P-ARDL cannot capture nonlinear relationships.

**Future Research:**

- ✓ Use disaggregated indices (e.g., R&D spending, patent quality).
- ✓ Apply advanced methods (quantile regression, structural causal models).
- ✓ Conduct country-specific studies (e.g., Iran) with micro-data.
- ✓ Compare developed vs. developing countries.

**Conclusion**

This study confirms that ICT significantly drives technological innovation in 15 developing countries, with FD and HDI mediating 28% and 35% of the effect, respectively. HDI's stronger role underscores the importance of human capital in resource-constrained settings. Policymakers should adopt integrated strategies:

- ✓ Enhance ICT infrastructure (broadband, cybersecurity).
- ✓ Reform financial systems to support innovation funding.
- ✓ Prioritize education and health to build innovation capacity.

These findings highlight innovation as a multifaceted phenomenon requiring coordinated investments in technology, finance, and human capital for sustainable growth in developing economies.

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**Authors' Contributions**

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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