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Exploring ICT as an Engine for Sustainable Economic Growth in Central Asia

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Abstract

This study investigates whether information and communication technology (ICT) constitutes a sustained driver of economic growth in four Central Asian economies—Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan—over the period 2000–2022. Using an extended endogenous growth framework, this study employs the following long-run growth model: economic growth is specified as a function of ICT development, gross capital formation, trade openness, human capital, government effectiveness, and inflation. A composite ICT index is constructed using Principal Component Analysis (PCA). Long-run relationships are examined using a panel cointegration approach, and long-run elasticities are estimated using FMOLS, DOLS, and CCR techniques. The results reveal that ICT development exerts a negative and statistically significant effect on economic growth in the long run, indicating limited technological absorptive capacity and insufficient institutional readiness in the region. In contrast, capital formation, trade openness, human capital, and government effectiveness positively and significantly promote growth, while inflation hampers economic performance. The findings suggest that ICT investment alone is insufficient for sustainable growth without complementary institutional strengthening, human capital development, digital skills enhancement, improved broadband quality, and governance reforms to increase the productive use of ICT.

Keywords: information and communication technology (ICT); economic growth; Central Asia; FMOLS; DOLS; CCR; cointegration analysis

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1. Introduction

Over the past three decades, the global economic system has undergone a profound transformation driven by the rapid diffusion of Information and Communication Technologies (ICTs) (A. Khan & Wu, 2022). The expansion of broadband infrastructure, the widespread adoption of mobile technologies, and the emergence of digital platforms have positioned ICT as a central pillar of productivity enhancement, innovation, and long-term

economic growth (Chatterjee, 2020). As a recognized general-purpose technology, ICT fundamentally reshapes production processes, market coordination, and competitive structures across economies (Saba et al., 2023). In advanced economies, digital technologies are deeply integrated into industrial systems, financial markets, and public administration, generating sustained efficiency gains and innovation-driven growth (Appiah-Otoo & Song, 2021).

Despite the growing body of international evidence on the ICT–growth nexus, there is still no clear consensus on whether ICT acts as a sustained long-run driver of economic growth in post-transition economies characterized by weak institutions, limited absorptive capacity, and uneven digital development, such as those of Central Asia. Existing studies largely focus on advanced or large emerging economies, while Central Asia remains empirically underexplored and theoretically ambiguous. Moreover, the majority of prior studies rely on single ICT indicators and short-run specifications, offering limited insight into the long-run growth dynamics of digitalization in institutionally constrained environments.

This creates a clear and unresolved empirical research problem: Does ICT generate durable long-term economic growth in Central Asia, or are its effects conditional on complementary structural and institutional factors?

To address this problem, the present study is guided by the following three core research questions:

RQ1: Does ICT development exert a statistically significant and long-run effect on economic growth in Central Asian economies?
RQ2: Is the impact of ICT on economic growth conditional on complementary factors such as human capital, government effectiveness, trade openness, and capital formation?
RQ3: Does the use of a multidimensional composite ICT index alter the magnitude and direction of the ICT–growth relationship compared with conventional single-indicator approaches used in prior studies?

By explicitly addressing these questions, this study moves beyond descriptive digitalization trends and provides a rigorous long-run econometric evaluation of the ICT–growth nexus in post-transition economies.

The Central Asian economies—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—provide a unique empirical setting to examine this unresolved relationship. Following the dissolution of the Soviet Union in 1991, these countries inherited centrally planned economic systems, obsolete industrial foundations, and limited technological bases. Since then, they have pursued heterogeneous development paths characterized by varying degrees of market liberalization, digital modernization, and institutional restructuring. National programs such as Kazakhstan's Digital Kazakhstan and Uzbekistan's Digital Economy Strategy reflect a strategic shift toward ICT-led diversification away from excessive reliance on natural resources. Similarly, Kyrgyzstan's Taza Koom ("Clean Society") initiative aims to digitalize public services and enhance connectivity in remote regions. However, progress across the region remains markedly uneven. While Kazakhstan and Uzbekistan demonstrate relatively advanced broadband penetration and digital governance frameworks, Tajikistan and Turkmenistan continue to face substantial constraints related to weak infrastructure, limited market competition, and institutional inefficiencies.

These asymmetries underscore a fundamental development challenge confronting Central Asia: how to convert rapid digital expansion into sustained, inclusive, and productivity-driven economic growth in the presence of persistent structural rigidities, institutional fragilities, and innovation deficits. From the standpoint of endogenous growth theory, long-term economic expansion is driven by internally generated forces such as technological progress, knowledge accumulation, innovation, and human capital formation (Adelakun et al., 2025). Within this framework, ICT plays a catalytic role by accelerating information diffusion, improving inter-market coordination, lowering transaction costs, and strength-

ening knowledge spillovers through network externalities. Moreover, ICT contributes to human capital accumulation by broadening access to education, digital skills, and information flows, thereby enhancing labor productivity and adaptive capacity in an increasingly digitalized economy (Karaman Aksentijević et al., 2021).

Nevertheless, the extent to which these theoretical growth-enhancing channels materialize in practice is highly contingent on the broader institutional, infrastructural, and governance environment. In developed economies, where institutional quality and digital infrastructure are well established, ICT investments typically translate into immediate and persistent productivity improvements. By contrast, in developing and post-transition economies such as those in Central Asia, ICT-induced growth effects may be substantially constrained by digital divides, weak regulatory systems, limited competition, inadequate human capital, and governance shortcomings. Despite the near-universal diffusion of mobile technologies, broadband accessibility, digital literacy, and the productive use of ICT remain uneven across the region. In several countries, dominant state control over telecommunications markets and weak competitive pressures continue to hamper innovation, affordability, and service quality.

These conditions give rise to a central empirical question: Can ICT function as a durable engine of economic growth in Central Asia, or does its impact remain conditional, fragmented, and institution dependent?

The existing empirical literature offers inconclusive and heterogeneous findings. A substantial body of research, including Röller and Waverman (2001), Vu (2011), and Niebel (2018), documents positive growth effects of ICT, particularly after economies achieve certain levels of digital maturity. Comparable evidence from Sub-Saharan Africa and Southeast Asia suggests that ICT enhances productivity, financial inclusion, and trade integration. However, most of this evidence is derived from large emerging markets or rapidly industrializing countries. In contrast, Central Asia remains largely underrepresented in the ICT–growth literature. Moreover, the few studies that include the region often treat ICT as an auxiliary variable within broader globalization or innovation frameworks rather than as a core long-run growth determinant. Consequently, the long-run nature and strength of the ICT–growth relationship in Central Asia remain empirically unsettled, particularly within a rigorous panel cointegration setting.

Filling this gap holds significant academic and policy relevance. Central Asian governments increasingly regard digital transformation as a cornerstone of their long-term development strategies, with the objective of fostering economic diversification, enhancing productivity, and strengthening global economic integration. Yet, in the absence of robust empirical evidence on the long-run growth effects of ICT, digital policy initiatives risk being inefficiently targeted or inadequately sequenced. If ICT is confirmed as a genuine long-term growth driver, strategic investments in digital infrastructure, skills development, and digital governance can substantially amplify growth outcomes. Conversely, if its effects are shown to be limited or conditional, deeper institutional and structural reforms become indispensable for unlocking its growth potential. Motivated by these concerns, the primary objective of this study is to empirically assess whether ICT acts as a sustained driver of economic growth in Central Asia over the period 2000–2022. The study adopts a multidimensional approach to ICT measurement, encompassing indicators related to internet usage, mobile connectivity, broadband access, and ICT-related trade. A composite ICT index is constructed to reflect the multifaceted nature of digital development, and advanced panel econometric methods, namely Fully FMOLS, DOLS, and CCR, are employed to estimate long-run elasticities within a panel cointegration framework.

The originality of this study is threefold. First, it delivers one of the few region-specific, long-horizon empirical analyses of the ICT–growth nexus focused exclusively

on Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan, thereby addressing a critical geographical gap in the literature. Second, by constructing a composite ICT index using Principal Component Analysis (PCA), the study provides a more comprehensive and nuanced representation of digital development than conventional single-indicator measures. Third, the application of three complementary panel cointegration estimators enhances the robustness and credibility of the findings by mitigating concerns related to endogeneity, serial correlation, and small-sample bias. Beyond its methodological contributions, the study generates important policy insights by identifying which dimensions of ICT-such as broadband diffusion, digital skills, regulatory quality, and institutional effectiveness-are most crucial for achieving sustained growth.

Overall, this study contends that, although ICT possesses substantial potential to serve as a long-term engine of economic growth in Central Asia, its effectiveness is fundamentally dependent on complementary investments in human capital, institutional capacity, and innovation ecosystems. As the region continues to advance ambitious digital transformation agendas through initiatives such as Digital Kazakhstan and Taza Koom, rigorous empirical evidence on the long-run ICT–growth nexus is essential for guiding effective, evidence-based policy design.

The remainder of the study is structured as follows. Section 2 reviews the relevant empirical literature on ICT and economic growth with an emphasis on developing and transition economies. Section 3 presents the theoretical framework and empirical model specification. Section 4 outlines the econometric methodology and estimation techniques. Section 5 reports and discusses the empirical findings. Sections 6 and 7 conclude with the main policy implications and avenues for future research.

2. Literature Review

A considerable volume of empirical research has explored the impact of infrastructure on economic growth, particularly since the late 1980s. Bougheas et al. (2000) argued that infrastructure, including telecommunications, operates as a cost-reducing technology that enhances overall productivity and efficiency. Kheng Soon (2012) emphasized that the influence of ICT on economic growth manifests through knowledge generation, human capabilities, and institutional structures. Similarly, Czernich et al. (2011) suggested that ICT enhances growth by fostering entrepreneurship, improving labor market efficiency, intensifying competition, and facilitating the diffusion of ideas and information. They further posited that ICT promotes economic expansion through knowledge spillovers across firms and industries. Kankaria and Dutta (2021) added that ICT usage reduces coordination costs, accelerates information dissemination, and improves access to services such as education and healthcare, thereby strengthening human capital and promoting long-term economic growth.

A substantial body of empirical research underscores the pivotal role of ICT in fostering economic growth across countries at varying stages of development; however, the magnitude and channels of this effect differ depending on institutional quality, income level, and digital infrastructure. These contrasts indicate that ICT's growth effect is context-specific and highlights the need for multidimensional ICT measures rather than single proxies.

Appiah-Otoo and Song (2021), analyzing 123 countries from 2002 to 2017, found that ICT-measured through mobile, internet, and broadband usage-positively influences economic growth in both high- and low-income economies, with stronger effects observed in less developed nations, suggesting that ICT accelerates technological diffusion and productivity improvements. Similarly, Awad and Albaity (2022) examined 44 Sub-Saharan African countries from 2004 to 2020 using panel-corrected standard errors and a two-step system GMM approach, revealing that ICT not only contributes directly to economic growth

but also exerts indirect effects through education, domestic investment, and trade openness. Complementing these findings, Toria Nipo et al. (2022) studied 20 Asian countries between 2000 and 2020 and showed that mobile subscriptions and internet usage significantly boost growth, while fixed telephone lines have become economically irrelevant, reflecting the shift toward digital connectivity.

Kurniawati (2021) further confirmed this heterogeneity by analyzing 25 high- and middle-income Asian countries (2000–2018) through panel cointegration techniques, finding that internet penetration drives growth in high-income economies, whereas mobile and telephone networks are more influential in middle-income contexts. In South Asia, Hussain et al. (2021) identified a long-run positive relationship between ICT penetration and growth in four countries (1995–2016), with internet use having the most substantial impact, supporting the leapfrogging hypothesis that developing nations can bypass traditional stages of technological development through digital adoption. Similarly, Sinha and Sengupta (2019) demonstrated that ICT expansion and foreign direct investment (FDI) jointly enhance growth across 30 developing Asia-Pacific countries, and that ICT also attracts FDI inflows, reinforcing its dual role as a catalyst for productivity and investment. Collectively, these studies establish that ICT is a key driver of modern economic transformation, enhancing productivity, human capital, and global integration, although its impact varies with institutional quality and development stage. Grounded in endogenous growth theory (Romer, 1994; Mattana, 2017), ICT fosters innovation, reduces transaction costs, and broadens information access, thereby promoting sustained economic growth. However, evidence from developing economies (Niebel, 2018; Ishida, 2015) cautions that inadequate infrastructure and weak institutional capacity may constrain ICT's benefits. Given the transitional nature of Central Asian economies, the direction and magnitude of ICT's growth effect remain empirically uncertain. Thus, the first hypothesis is formulated as follows:

H1. *ICT development has a significant long-term effect on economic growth in Central Asian economies.*

Gross fixed capital formation (GFCF) serves as a fundamental driver of economic growth, representing investments in physical assets that expand a nation's productive capacity and employment potential. A growing body of empirical research supports the view that capital accumulation plays a pivotal role in sustaining long-term economic development, though its magnitude and effectiveness often depend on institutional quality, governance structures, and macroeconomic stability. For example, Kesar et al. (2022) analyzed BRICS economies from 2002 to 2019 using fixed effects, Driscoll–Kraay estimators, and cointegration techniques, finding that GFCF, alongside governance effectiveness and control of corruption, significantly enhances economic growth. Their findings underscore the notion that investment-led growth is more pronounced in environments characterized by strong institutions and effective governance. Similarly, Mohsin et al. (2021) examined eight South Asian countries between 2000 and 2018 using fixed effects, quantile regression, and robust estimation methods, concluding that GFCF and trade openness exert positive impacts on growth, while excessive external debt impedes it. The study emphasized that domestic capital formation can help offset the negative consequences of foreign indebtedness, particularly in economies with resilient institutional frameworks. In the context of Belt and Road Initiative (BRI) economies, Zaman et al. (2021) applied a two-step system GMM approach on panel data from 2013 to 2018 and reported that GFCF and foreign direct investment (FDI) significantly bolster economic growth, reaffirming the complementary roles of domestic and international investment in sustaining development.

Collectively, these studies establish that while ICT is a key driver of modern economic transformation, its impact varies across regions, institutional contexts, and development

stages, leaving Central Asia relatively understudied. However, evidence from developing economies cautions that inadequate infrastructure and weak institutional capacity may constrain ICT's benefits, a nuance rarely explored in post-Soviet economies. These studies indicate that the interplay between physical capital and institutional quality is crucial, yet this interaction remains underexplored in transitional economies.

Within both neoclassical and endogenous growth frameworks (Solow, 1957; Mankiw et al., 1992), physical capital accumulation enhances productive capacity and complements technological advancement, thereby sustaining long-run growth. Empirical findings across different contexts (Bougheas et al., 2000) further corroborate the positive linkage between capital formation and output growth. Hence, the second hypothesis is proposed as:

H2. *Gross capital formation has a positive and significant impact on economic growth in Central Asian economies.*

Human capital, encompassing both educational attainment and health status, represents a fundamental pillar of sustained economic growth, as it enhances labor productivity, stimulates innovation, and facilitates the absorption and diffusion of new technologies. However, its contribution to economic growth is not uniform across countries; it varies according to the level of development, institutional quality, and the efficiency of public investment in education and health. Sultana et al. (2022), employing panel data for 141 countries from 1980 to 2008 and using the System Generalized Method of Moments (SGMM) estimator, found that human capital exerts a strong and positive influence on economic growth in developing countries, particularly through improvements in life expectancy, which reflect enhanced health outcomes and demographic transition. In contrast, in developed economies, extended life expectancy was associated with slower growth, potentially due to aging populations and increasing dependency ratios.

In emerging and developing regions, the contribution of human capital to economic growth is more complex and shaped by structural and institutional factors. For example, Rahman et al. (2022) investigated the role of human capital, financial development, and energy consumption in six ASEAN countries (Cambodia, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam) over the period 1995–2017, employing second-generation panel econometric techniques that account for cross-sectional dependence and heterogeneity. Their results indicate that human capital significantly promotes economic growth in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, confirming its indispensable role in sustaining long-term development. However, the study also revealed that ASEAN economies remain largely dependent on physical capital and labor, suggesting that the full potential of human capital has yet to be realized. Moreover, the causality analysis showed that while human capital exerts a growth-enhancing effect, the strength and direction of this relationship differ across countries depending on their structural characteristics and policy environments.

These findings are consistent with the broader empirical consensus that human capital functions as both a direct and indirect catalyst for economic growth. Directly, it raises productivity; indirectly, it supports other growth drivers such as financial development, innovation, and energy efficiency. Pelinescu (2015) and Jahanger et al. (2022) similarly found that human capital contributes to sustainable economic development by improving labor productivity and facilitating the adoption of cleaner, technology-based production methods. Moreover, human capital enhances the absorptive capacity of economies, enabling them to benefit more effectively from globalization, foreign investment, and technological spillovers.

Supporting this perspective, Abdouli and Omri (2020) examined the relationship between human capital, foreign direct investment (FDI), environmental quality, and economic

growth in the Mediterranean region from 1990 to 2013, using dynamic OLS (DOLS) and fully modified OLS (FMOLS) estimation techniques. Their analysis revealed a bidirectional causal relationship between human capital and economic growth across most regional panels, confirming the mutually reinforcing nature of this linkage. In a related study, M. T. I. Khan et al. (2023) explored the role of human capital alongside infrastructure, FDI, globalization, and capital formation in the disaster–growth nexus across 98 countries, categorized into four income groups, from 1995 to 2019. By constructing a composite human capital index and employing a two-step generalized method of moments (GMM) approach, they found that human capital significantly contributes to economic growth across all income groups. The findings emphasize that economies with higher levels of education, skills, and health are better positioned to mitigate the adverse economic effects of natural disasters.

Nonetheless, the magnitude of the impact of human capital on economic growth ultimately depends on the quality of education systems, the efficiency of health investments, and the alignment between skills development and labor market demands. Therefore, the following hypothesis is proposed:

H3. *Human capital development positively contributes to economic growth in Central Asian economies.*

The relationship between trade openness and economic growth remains one of the most debated issues in development economics, as empirical outcomes differ across countries depending on structural characteristics, institutional quality, and stages of development. Jalil and Rauf (2021), analyzing 82 countries from 1960 to 2019 using the Common Correlated Effects Mean Group (CCEMG) estimator and the System Generalized Method of Moments (GMM), found robust evidence that trade openness consistently promotes economic growth, even after addressing endogeneity, cross-sectional dependence, and structural breaks. Their results suggest that liberalized trade policies improve resource allocation, enhance technology transfer, and boost market efficiency, thereby supporting the long-term growth effects of globalization. Similarly, Nam and Ryu (2024) examined ASEAN economies and highlighted the nuanced effects of trade openness by differentiating between trade barriers and trade volumes. While greater trade volumes significantly stimulated GDP growth, excessively low trade barriers sometimes hindered growth in developing economies, implying that the benefits of openness are conditional upon industrial capacity and institutional strength. Conversely, Soomro et al. (2022), focusing on BRICS economies from 2000 to 2018, reported that trade openness and foreign direct investment had negative effects on growth, whereas information and communication technology (ICT) infrastructure exerted a positive influence. Their findings underscore that premature or unbalanced liberalization, without sufficient technological or structural readiness, may weaken domestic industries and reduce competitiveness. Complementary evidence from Nguyen et al. (2023), who analyzed 20 Asian economies between 2011 and 2019, revealed that while trade openness negatively affected growth stability, it enhanced exchange rate stability in the short run-illustrating its complex macroeconomic implications. Taken together, these studies suggest that trade openness can serve as a powerful engine of long-term economic growth through increased efficiency, specialization, and global integration, yet it also exposes developing economies to external shocks and short-term volatility. Furthermore, endogenous growth theory (Grossman & Helpman, 1991) also mentioned that trade openness fosters innovation and productivity growth by facilitating knowledge spillovers and technology diffusion across borders. Empirical research across developing regions similarly supports a positive and significant link between openness and economic performance (Keho, 2017; Kpomblekou & Wonyra, 2020; Kong et al., 2021;

Manwa et al., 2019; Salahuddin & Gow, 2016). Accordingly, the study formulates the following hypothesis:

H4. *Trade openness exerts a positive and significant effect on economic growth in Central Asian economies.*

The relationship between inflation and economic growth has remained a central issue in macroeconomic research, particularly in developing economies where achieving price stability is essential for sustaining long-term growth. Uddin and Rahman (2022), using data from 79 developing countries between 2002 and 2018 and employing Pooled Mean Group (PMG), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS) estimators, found that inflation-alongside governance effectiveness and rule of law-positively influences GDP per capita. Their results suggest that moderate inflation can stimulate productive investment and economic activity when accompanied by sound institutional frameworks. Conversely, corruption, unemployment, and political instability were shown to exert negative effects, underscoring the necessity of institutional and macroeconomic stability. Complementing these findings, Tien (2021) investigated Vietnam's inflation-growth relationship and revealed a nonlinear threshold effect, whereby inflation above 6 percent significantly hinders GDP growth. The study concluded that while mild inflation encourages spending and investment, high inflation erodes purchasing power, distorts resource allocation, and ultimately impedes growth. Similarly, Rosnawintang et al. (2020), analyzing ASEAN-5 economies from 1995 to 2018, reported that inflation's impact on growth was short-term and country-specific, with positive effects evident in nations such as Indonesia, the Philippines, Singapore, and Thailand. These findings highlight that the inflation-growth nexus is context-dependent, shaped by institutional quality, macroeconomic management, and structural characteristics. Consistent with theoretical expectations, moderate and stable inflation tends to support economic growth, whereas excessive or volatile inflation undermines it, especially in developing economies with fragile financial systems (Barro, 1995; Islam, 2024). Macroeconomic stability thus emerges as a precondition for sustained economic expansion, as high inflation distorts investment decisions, weakens confidence, and constrains long-term growth. Thus, the hypothesis is stated as:

H5. *Inflation has a negative and significant impact on economic growth in Central Asian economies.*

Government effectiveness is a key determinant of economic growth, as it shapes the efficiency of policy implementation, resource allocation, and public service delivery. Empirical evidence consistently highlights the role of effective governance in fostering stable and sustainable economic performance. Hang and Lien (2022), analyzing data from 49 high-, middle-, and low-income countries between 2000 and 2019 using a two-stage least squares (2SLS) model, found that the impact of government effectiveness on growth is multidimensional. While control of corruption exerts a positive and significant effect on income per capita, higher tax revenue negatively influences growth, suggesting that the quality of governance and fiscal efficiency are crucial for maximizing economic outcomes. The study further established that monetary policy and trade openness have strong positive effects on growth, reinforcing the idea that institutional efficiency enhances the transmission of macroeconomic policies. Similarly, Al-Naser and Hamdan (2021), employing a fixed-effects model for six Gulf Cooperation Council (GCC) countries from 1996 to 2019, reported that government effectiveness and regulatory quality significantly promote economic growth, while the effects of control of corruption and rule of law, though positive, were statistically insignificant. Their results underscore that policy credibility and administrative efficiency are vital channels through which governance influences economic performance.

Collectively, these findings demonstrate that the quality of governance, especially in terms of policy implementation and regulatory frameworks, enhances productivity, investment, and innovation, although its effects may vary depending on governance dimensions and regional characteristics. Strong institutional quality and effective governance also facilitate the productive use of economic resources and technological investments by ensuring transparency, accountability, and policy coherence (Kaufmann et al., 2011). Empirical studies (Adeleye et al., 2023; Sabir et al., 2019) further confirm that improved governance not only promotes economic growth directly but also strengthens the effectiveness of ICT and other development-enhancing factors. Therefore, the sixth hypothesis is proposed as:

H6. *Government effectiveness positively and significantly influences economic growth in Central Asian economies.*

Furthermore, recent empirical studies emphasize the growing interdependence between financial systems, technological development, and environmental sustainability. Bagci et al. (2025) demonstrate that agricultural support policies and financial institutions significantly shape greenhouse gas emissions in emerging economies, particularly highlighting the mitigating role of financial institutions in Türkiye and South Africa through sustainable investment channels. Their findings underscore the importance of institutional quality and environmentally oriented financial mechanisms in achieving greener growth outcomes. Complementing this perspective, Aydin et al. (2025) examine the ecological impacts of renewable energy, investment freedom, and ICT in Denmark, revealing that, while renewable energy and investment freedom enhance ecological sustainability, ICT penetration may exert a negative environmental effect if not efficiently managed. This suggests that ICT alone does not guarantee sustainability unless aligned with green energy and investment frameworks. Meanwhile, Destek et al. (2025) provide evidence from the United States that financial deepening-particularly through business loans-can intensify carbon emissions by channeling credit toward carbon-intensive production, whereas household loans exhibit no significant environmental impact. Collectively, these studies indicate that economic growth, finance, and ICT can either support or hinder environmental sustainability depending on institutional structures, sectoral allocation of finance, and the integration of green technologies. For Central Asian economies, this literature implies that ICT can serve as a powerful engine for sustainable economic growth only when supported by environmentally responsible financial systems, effective institutions, and green investment strategies.

Despite the extensive empirical evidence on ICT, capital formation, human capital, trade openness, inflation, and government effectiveness, prior studies largely examine these factors in isolation and focus predominantly on developed, BRICS, ASEAN, or African economies. Very limited empirical research has jointly analyzed these growth drivers within a unified framework for Central Asian transition economies, particularly accounting for the interaction between ICT development and institutional quality. This unresolved gap motivates the present study.

3. Theoretical Framework

The empirical analysis in this study is theoretically motivated by endogenous growth theory, which emphasizes the role of knowledge accumulation, human capital, and technology in driving long-term economic growth (Romer, 1994; Lucas, 1988). In this context, ICT is considered a productivity-enhancing factor that can facilitate technological spillovers, knowledge diffusion, and innovation, thereby contributing to growth beyond the effects of physical and human capital alone. Human capital and institutional quality are included as complementary factors that support the effective adoption and utilization of ICT, enabling

its potential to enhance productivity and economic performance. While the scope of this study and data availability do not allow for the development of a full formal theoretical model, the empirical specification reflects the core mechanisms proposed by endogenous growth theory, providing a conceptual foundation that links ICT, capital accumulation, governance, and economic growth in Central Asian economies (Solow, 1957; Metcalfe, 2010).

According to the ICT-led growth hypothesis, ICT contributes to economic performance through several channels. First, it acts as a productivity-enhancing technology, enabling firms to optimize production processes and improve market competitiveness (Czernich et al., 2011). Second, ICT stimulates knowledge spillovers and innovation diffusion, particularly in economies transitioning from resource-based to knowledge-based structures (Röller & Waverman, 2001). Third, it supports institutional efficiency and governance quality by improving transparency, administrative effectiveness, and public service delivery (Baliamoune-Lutz, 2003). Finally, ICT investment strengthens human capital formation by expanding access to education and digital skills (Chavula, 2012).

In the context of Central Asian economies, the theoretical relevance of ICT is particularly salient. These economies have been undergoing a structural transformation from centrally planned systems toward more market-oriented frameworks, where digitalization is emerging as a key enabler of modernization and regional competitiveness. The ICT infrastructure in countries such as Kazakhstan and Uzbekistan has expanded substantially over the past two decades, with increasing broadband and mobile penetration (Kurmanov et al., 2025). However, disparities in digital readiness and institutional capacity persist, particularly in Kyrgyzstan and Tajikistan, where connectivity and governance challenges constrain the potential productivity gains from ICT adoption.

Building on the Solow–Swan production function, this study extends the traditional model to incorporate ICT as a factor of production alongside capital and labor. The augmented model assumes that ICT contributes not only directly to output but also indirectly through its interaction with human capital, trade openness, and institutional efficiency. Thus, economic growth (Y) in country i at time t can be expressed as a function of ICT development (ICT), gross capital formation (GCF), human capital (HC), trade openness (Trade), inflation (INF), and government effectiveness (GOVEF). The theoretical relationship can be represented as follows:

$$Y_{it} = f(I, C, T_{it}, G, C, F_{it} HC_{it} Trade_{it} INF_{it} GOVEF_{it})$$

This framework implies that ICT-driven growth depends not only on the expansion of digital infrastructure but also on the complementary role of human and physical capital, macroeconomic stability, and institutional quality. In the absence of these enabling conditions, ICT's contribution to growth may be limited or even negative due to inefficiencies in adoption and governance (Niebel, 2018; Grunwald, 2017).

4. Data and Methodology

4.1. Model Specification

Based on the theoretical framework, the empirical model adopts a log-linear specification to capture elasticities between ICT development and economic growth. The baseline model is expressed as:

$$\ln GDP_{it} = \alpha_i + \beta_1 ICT_{it} + \beta_2 \ln GCF_{it} + \beta_3 \ln HC_{it} + \beta_4 \ln Trade_{it} + \beta_5 \ln INF_{it} + \beta_6 GOVEF_{it} + \varepsilon_{it}$$

where:

$\ln GDP_{it}$: logarithm of real GDP per capita (proxy for economic growth),

ICT_{it}: ICT development index constructed using Principal Component Analysis (PCA) from variables such as internet users, mobile subscriptions, and broadband penetration,
$\ln GCF_{it}$: logarithm of gross capital formation (% of GDP), representing physical capital accumulation,
$\ln HC_{it}$: logarithm of human capital index (education-based measure),
$\ln Trade_{it}$: logarithm of trade openness (exports + imports as % of GDP),
$\ln INF_{it}$: logarithm of inflation rate (proxy for macroeconomic stability),
$GOVEF_{it}$: government effectiveness (institutional quality indicator),
α_i: country-specific fixed effects capturing unobserved heterogeneity,
ε_{it}: stochastic error term.

ICT Index Construction

A composite ICT Development Index was constructed using Principal Component Analysis (PCA) based on four key indicators of digital infrastructure and technological adoption: internet users (percentage of population), fixed broadband subscriptions (per 100 people), mobile cellular subscriptions (per 100 people), and secure internet servers (per million people). All indicators were standardized prior to analysis, and PCA was applied to extract the common latent dimension underlying these measures. The first principal component, which captures the majority of the total variance across indicators, was retained and used as the ICT Index, with weights determined by the component loadings. This approach provides a statistically rigorous and data-driven measure that summarizes overall ICT development across countries under the study.

The correlation matrix which is shown in Table 1 reveals consistently strong and positive associations among all four ICT indicators (internet users, fixed broadband subscriptions, mobile cellular subscriptions, and secure servers) with correlation coefficients ranging from 0.65 to 0.84. This pattern suggests that the indicators share substantial common variance and capture interconnected dimensions of digital development. The strongest correlations appear between internet users and broadband (0.84) and between internet users and secure servers (0.81), reflecting that higher levels of digital access tend to coincide with more advanced network infrastructure and online security. These high correlations indicate that the variables are well suited for dimension-reduction techniques such as PCA, as they measure related aspects of a latent ICT construct.

Table 1. Correlation matrix for ICT index indicators.

	Internet Users	**Broadband**	**Mobile Subscriptions**	**Secure Servers**
Internet Users	1.00	0.84	0.72	0.81
Broadband	0.84	1.00	0.65	0.78
Mobile Subscriptions	0.72	0.65	1.00	0.69
Secure Servers	0.81	0.78	0.69	1.00

The eigenvalue structure in Table 2 provides strong justification for retaining only the first principal component (PC1). PC1 has an eigenvalue of 3.11 and explains 77.8% of the total variance, far exceeding the Kaiser criterion of eigenvalues greater than one. The remaining components each explain less than 12% of the variance, indicating that they contribute little additional information. The cumulative explained variance for PC1 (77.8%) demonstrates that the four indicators are driven by a single dominant underlying factor, which can be interpreted as overall ICT development.

Table 2. Eigenvalues and variance explained.

Component	Eigenvalue	Variance Explained (%)	Cumulative (%)
PC1	3.11	77.8%	77.8%
PC2	0.48	12.0%	89.8%
PC3	0.26	6.4%	96.2%
PC4	0.15	3.8%	100%

According to the Table 3, the component loadings for PC1 (0.92 (internet users), 0.88 (broadband), 0.80 (mobile subscriptions), and 0.90 (secure servers)) are all high and exceed conventional thresholds for strong factor loadings (>0.70). This confirms that each indicator contributes meaningfully to the extracted latent dimension and that PC1 effectively captures the shared digital infrastructure and usage characteristics across countries.

Table 3. Component (factor) loadings for PC1.

Indicator	Loading on PC1
Internet Users	0.92
Fixed Broadband	0.88
Mobile Subscriptions	0.80
Secure Servers	0.90

Robustness checks given in Table 4 support the stability of the index. Using an alternative normalization method (min–max scaling) yields a nearly identical structure, with PC1 still explaining 75.9% of the variance and correlating 0.97 with the baseline index. Leave-one-indicator-out tests produce correlations between 0.92 and 0.96, showing that no single variable disproportionately drives the composite index. Similarly, missing value imputation does not materially affect the factor loadings, further reinforcing the reliability of the PCA-derived index.

Table 4. Robustness checks.

Robustness Test	Result
Alternative normalization (min–max)	PC1 explains 75.9% variance; index correlation with baseline 0.97
Leave-one-indicator-out	Correlation with baseline index 0.92–0.96
Missing value imputation	No material change in factor loadings

The PCA diagnostic tests in Table 5 further confirm suitability. The Kaiser–Meyer–Olkin (KMO) value of 0.82 exceeds the recommended threshold of 0.70, indicating strong sampling adequacy. Likewise, Bartlett's Test of Sphericity is significant (χ^2 = 294.6, $p < 0.001$), rejecting the null hypothesis of no correlation and validating the use of PCA on these variables.

Table 5. PCA Diagnostic Tests.

Diagnostics Tests	Statistics
Kaiser–Meyer–Olkin (KMO) Test	0.82
Bartlett's Test of Sphericity	294.6 ***

Note: *** $p < 0.01$.

4.2. Estimation Techniques

Given that the dataset comprises a small number of countries (N = 4) observed over a relatively long time span (T = 23 years), the study adopts panel cointegration techniques suitable for small-sample panels. After establishing the presence of panel cointegration among the variables through Pedroni (1999) test, three long-run estimators are employed: FMOLS, DOLS, and CCR.

The FMOLS estimator (Phillips & Hansen, 1990) corrects for serial correlation and endogeneity biases inherent in cointegrated systems by adjusting both the dependent and independent variables. The DOLS estimator (Stock & Watson, 1993) further addresses endogeneity by including leads and lags of the differenced regressors, providing efficient long-run parameter estimates. The CCR estimator (Park, 1992) transforms the data to remove long-run correlation between the error term and the regressors, ensuring consistent and asymptotically efficient results. Employing all three estimators enhances robustness and comparability of long-run coefficients.

4.3. Data and Variable Construction

The study utilizes an annual panel dataset covering four Central Asian economies, Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan, over the period 2000 to 2022. The dependent variable, real GDP per capita (in logarithmic form), serves as a proxy for economic growth. The principal explanatory variable, the ICT development index, is constructed through PCA by aggregating multiple ICT indicators, including internet users, fixed broadband subscriptions, mobile cellular subscriptions, and secure servers. These data are obtained from the World Development Indicators (WDI) of the World Bank (Table 6). The model further incorporates several control variables commonly associated with economic growth in empirical literature: physical capital accumulation (gross capital formation), human capital (tertiary school enrollment, gross %), trade openness, inflation rate, and institutional quality (government effectiveness). All variables are transformed into natural logarithms to ensure scale comparability, reduce heteroskedasticity, and allow the estimated coefficients to be interpreted as elasticities.

Table 6. Variable description, measurement, and data sources.

Variable	Symbol/ Transformation	Measurement/Definition	Data Source	Years Covered
Economic Growth	lnGDP	Natural logarithm of real GDP per capita (constant 2015 USD)	World Development Indicators (WDI, World Bank)	2000–2022
ICT Development Index	ict_index_pca	Composite index constructed via Principal Component Analysis (PCA) of: (i) internet users (% of population), (ii) fixed broadband subscriptions (per 100 people), (iii) mobile cellular subscriptions (per 100 people), and (iv) secure servers (per million people).	World Development Indicators (WDI, World Bank)	2000–2022
Gross Capital Formation	lnGCF	Natural logarithm of gross capital formation (% of GDP), proxy for physical capital accumulation.	World Development Indicators (WDI, World Bank)	2000–2022

Table 6. *Cont.*

Variable	Symbol/ Transformation	Measurement/Definition	Data Source	Years Covered
Human Capital Index	lnHC	Natural logarithm of school enrollment, tertiary (% gross), serving as a proxy for the educational attainment and skill level of the labor force.	World Development Indicators (WDI, World Bank)	2000–2022
Trade Openness	lnTrade	Natural logarithm of total trade (exports + imports) as a percentage of GDP.	World Development Indicators (WDI, World Bank)	2000–2022
Inflation Rate	lnInf	Natural logarithm of annual consumer price index (CPI, % change). Proxy for macroeconomic stability.	World Development Indicators (WDI, World Bank)	2000–2022
Government Effectiveness	GovEf	Index measuring the quality of public services, policy formulation, and implementation (ranges from −2.5 to +2.5).	Worldwide Governance Indicators (WGI, World Bank)	2000–2022

The selection of variables in this study is guided by both theoretical considerations and precedent in the empirical literature on economic growth. The dependent variable, real GDP per capita (in logarithmic form), is employed as a widely accepted proxy for economic growth, allowing for cross-country comparability and interpretation in elasticity terms. The principal explanatory variable, the ICT Development Index, is constructed using Principal Component Analysis (PCA) to aggregate multiple dimensions of digital infrastructure and technological adoption, including internet users, fixed broadband subscriptions, mobile cellular subscriptions, and secure servers. These indicators capture access, connectivity, and digital security aspects of ICT, providing a comprehensive measure of technological development. Data for ICT indicators are sourced from the World Development Indicators (WDI) database of the World Bank, ensuring reliability and consistency.

The model also incorporates several control variables commonly associated with economic growth. Physical capital accumulation, measured by gross capital formation, reflects investment in productive assets. Human capital is proxied by gross tertiary school enrollment, capturing formal educational attainment; this measure emphasizes the accumulation of advanced skills in the labor force, which are critical for adopting and effectively utilizing modern technologies, including ICT. While it does not fully capture quality or digital competencies, it represents a widely used indicator in cross-country growth studies. Trade openness reflects the extent of integration into global markets, influencing knowledge transfer and productivity gains. Inflation serves as a proxy for macroeconomic stability, which can affect investment and growth outcomes. Institutional quality is captured by the Government Effectiveness indicator, which measures the capacity of public institutions to formulate and implement policies, deliver public services, and maintain a stable environment for economic activity. High government effectiveness facilitates the productive use of both physical and human capital, as well as the diffusion of ICT across sectors.

All variables are transformed into natural logarithms to improve comparability across scales, reduce heteroskedasticity, and facilitate interpretation of coefficients as elasticities. Collectively, these variables provide a theoretically grounded and empirically validated framework for analyzing the impact of ICT and other structural factors on economic growth

in Central Asian economies, while highlighting the roles of human capital development and institutional quality in supporting technological and economic progress.

Table 7 reports the descriptive statistics for the variables used in the analysis over the 2000–2022 period for four Central Asian economies. The mean value of the logarithm of real GDP per capita (lnGDP) is 7.81, indicating moderate variation in income levels across countries and years, with a standard deviation of 0.94. The ICT index, constructed through PCA, has a mean near 2.5 and a standard deviation of 1.57, reflecting standardized values around the mean and considerable variation in ICT development across the sample. Gross capital formation (lnGCF) exhibits an average value of 22.78, suggesting a stable investment level relative to output, while human capital (lnHC), proxied by tertiary enrollment, shows a mean of 3.44 with moderate dispersion. Trade openness (lnTrade) averages around 4.23, highlighting the region's moderate integration into global markets. Inflation (lnInf) displays higher variability, indicating occasional macroeconomic instability. Government effectiveness (GovEf) has a negative mean value (–0.62), implying relatively weak institutional performance in the region compared with global standards. Overall, the descriptive statistics suggest significant heterogeneity across the Central Asian economies in terms of ICT development, institutional quality, and macroeconomic structure-underscoring the relevance of a panel approach for capturing these dynamics.

Table 7. Descriptive Statistics.

Variable	Mean	Std. Dev.	Min	Max
lngdp	7.806599	0.9444916	6.647175	9.380097
ict_index	2.46787	1.565783	−2.055365	3.694072
lngcf	22.78085	1.410226	20.97582	25.06281
lnhc	3.437507	0.6544393	2.060455	4.131835
lntrade	4.225243	0.365648	3.373905	4.939325
lninf	2.00577	0.6954794	−0.9445917	2.863582
govef	−0.617224	0.3528767	−1.182448	0.1468147

Source: Computed by Stata 17.0.

Table 8 presents the pairwise correlation coefficients among the variables included in the model. The results show that economic growth (lnGDP) is positively and moderately correlated with ICT development (r = 0.71), gross capital formation (r = 0.78), and government effectiveness (r = 0.87), suggesting that improvements in technological infrastructure, investment, and institutional quality tend to be associated with higher levels of economic output. These findings are consistent with prior literature emphasizing the role of ICT and governance in promoting productivity and long-term growth (Czernich et al., 2011).

Table 8. Correlation matrix.

	lngdp	ict_index	lngcf	lnhc	lntrade	lninf	govef
lngdp	1.0000						
ict_index	0.7131	1.0000					
lngcf	0.7824	0.7116	1.0000				
lnhc	0.4533	0.6496	0.3464	1.0000			
lntrade	−0.5238	−0.2699	−0.6235	0.3914	1.0000		
lninf	0.2521	0.1800	0.2700	0.0367	−0.1486	1.0000	
govef	0.8680	0.6506	0.6355	0.5363	−0.3815	0.2644	1.0000

Source: Computed by Stata 17.0.

A moderate positive correlation between ICT Index and human capital (r = 0.65) reflects the complementary relationship between technological progress and education or

skill formation. Conversely, trade openness (lnTrade) displays negative correlations with GDP and investment, possibly indicating structural dependencies or trade concentration in specific commodities typical of Central Asian economies. Inflation (lnInf) exhibits weak correlations with most variables, implying limited contemporaneous interaction with real sector dynamics. Overall, the correlation results indicate that the variables are meaningfully related in directions consistent with theoretical expectations, and the degree of association does not suggest severe multicollinearity. This provides an initial indication that the variables are suitable for inclusion in the subsequent panel cointegration and long-run estimation procedures.

The results of the Fisher-type panel unit root tests based on the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) specifications are reported in Table 9. The null hypothesis of a unit root cannot be rejected for any variable at levels, indicating that all series are non-stationary in their original form. However, when the series are transformed into their first differences, the test statistics become highly significant at the 1% level across both ADF and PP versions, thereby rejecting the null hypothesis. These results suggest that all variables, including economic growth (lnGDP), ICT index, gross capital formation (lnGCF), human capital (lnHC), trade openness (lnTrade), inflation (lnInf), and government effectiveness (GovEf), are integrated of order one, I(1). The I(1) properties of the variables justify the application of panel cointegration techniques such as Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) to estimate the long-run relationships among ICT development and economic growth in Central Asian economies.

Table 9. Panel unit root test results.

	Fisher-ADF		Fisher-PP	
Variable	**Level**	**1st Differenced**	**Level**	**1st Differenced**
lngdp	0.7237	59.3551 ***	4.8393	38.5100 ***
ict_inde	0.3233	65.3467 ***	1.3322	85.1323 ***
lngcf	2.7937	14.8000 ***	1.4147	22.7013 ***
lnhc	4.7581	76.4016 ***	3.1129	17.7800 ***
lntrade	11.2309	23.1963 ***	6.6698	33.9443 ***
lninf	10.6123	20.4663 ***	10.8980	61.5130 ***
govef	5.1577	15.2658 ***	8.1657	29.2488 ***

Source: Computed by Stata 17.0, Note: Fisher-type unit root tests are based on the inverse chi-squared (2) distribution. Note: *** $p < 0.01$.

Table 10 demonstrates the Pedroni panel cointegration test, which accounts for both within- and between-dimension heterogeneity across Central Asian economies, provides strong evidence of a long-run equilibrium relationship among the variables. In the within-dimension results, the Panel v-, PP-, and ADF-statistics are all highly significant at the 1% level, suggesting cointegration when common time effects are considered. Similarly, the between-dimension (group) statistics confirm that the null of no cointegration can be rejected, further supporting the presence of a long-run association between economic growth, ICT development, and the control variables. These findings validate the use of long-run estimators such as FMOLS, DOLS, and CCR for the subsequent empirical analysis.

Table 10. Pedroni cointegration test results.

Pedroni Test Statistic	Value	*p*-Value
Within-Dimension (Panel Statistics)		
Panel v-Statistic	2.731	0.003
Panel rho-Statistic	−1.512	0.065
Panel PP-Statistic	−4.862	0.000
Panel ADF-Statistic	−3.714	0.000
Between-Dimension (Group Statistics)		
Group rho-Statistic	−0.947	0.082
Group PP-Statistic	−5.011	0.000
Group ADF-Statistic	−3.921	0.000

Source: Computed by Stata 17.0.

5. Empirical Results

Table 11 presents the long-run estimation results obtained through FMOLS, DOLS, and CCR techniques, which are employed to examine the enduring relationship between ICT development and economic growth across selected Central Asian economies during the period 2000–2022. These estimators are robust to potential issues of endogeneity, serial correlation, and small sample bias, providing reliable long-run parameter estimates in the presence of cointegration.

Table 11. Regression results of FMOLS and DOLS.

	(1)	(2)	(3)
VARIABLES	**FMOLS**	**DOLS**	**CCR**
ict_index	−0.172 ***	−0.169 ***	−0.168 ***
	(0.0250)	(0.0245)	(0.0258)
lngcf	0.803 ***	0.924 ***	0.809 ***
	(0.0298)	(0.0335)	(0.0368)
lnhc	0.368 ***	−0.00100	0.331 **
	(0.0814)	(0.156)	(0.160)
lntrade	0.243 **	0.717 ***	0.272 *
	(0.0945)	(0.149)	(0.143)
lninf	−0.0410 **	−0.102 ***	−0.0498
	(0.0207)	(0.0277)	(0.0306)
govef	0.424 ***	0.336 ***	0.426 ***
	(0.0831)	(0.0503)	(0.0978)
Constant	−12.63 ***	−16.04 ***	−12.73 ***
	(0.911)	(0.836)	(0.993)
Observations	35	33	35
R-squared	0.981	0.999	0.982

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The long-run coefficient of the ICT development index (ict_index) is negative and statistically significant across all three estimators (FMOLS, DOLS, and CCR), with an elasticity of approximately −0.17 in the FMOLS model. This indicates that, holding other factors constant, a 1% increase in ICT development leads to a 0.17% decline in economic growth among the Central Asian economies over the study period. Although this finding may initially appear counterintuitive, it is not uncommon in the empirical growth literature, particularly in the context of developing and transition economies where ICT infrastructure and institutional capacities remain in formative stages.

Several studies have reported similar outcomes, emphasizing that the growth-enhancing potential of ICT is contingent upon the presence of complementary factors

such as human capital, institutional quality, and absorptive capacity. For instance, Kuldasheva and Gress (2024), examining the main drivers of growth in landlocked Central Asian countries using FMOLS and DOLS techniques, found that ICT development has a negative and statistically significant impact on GDP per capita growth. The author attributes this result to weak digital readiness, low diffusion of ICT-based production technologies, and institutional barriers that prevent efficient use of digital infrastructure. This finding closely mirrors the pattern observed in the present study, suggesting that the ICT-growth relationship in Central Asia may be constrained by similar structural characteristics.

Empirical evidence from other developing regions further reinforces this interpretation. Haini (2021) concludes that ICT alone does not necessarily stimulate growth; rather, its impact becomes positive only when coupled with improvements in human capital and governance. Similarly, Alataş and Çakır (2016) find that ICT penetration negatively affects short-run economic growth in lower-income countries due to high import dependence, infrastructure costs, and limited domestic technological innovation. Niebel (2018), in a comprehensive study covering 59 economies, also observes that, while ICT capital contributes positively to growth in advanced economies, its effect in developing and emerging economies remains statistically insignificant or weakly positive, primarily due to insufficient absorptive capacity and institutional inefficiencies.

The negative elasticity found in this study may therefore reflect the transitional nature of Central Asian economies, where ICT expansion has outpaced the development of complementary factors needed to translate digitalization into productivity gains. In particular, the region faces challenges such as limited broadband quality, rural–urban digital divides, inadequate digital skills, and governance inefficiencies, all of which constrain the effective utilization of ICT in productive sectors. As Vu (2011) argues, ICT contributes to growth only after a critical threshold of technological capability and human capital accumulation is reached—a condition that many developing economies, including those in Central Asia, have yet to fully achieve. Furthermore, ICT investment in the region may currently be concentrated in consumption-oriented services rather than productive sectors such as manufacturing, finance, or logistics. This misallocation can lead to a temporary decline in growth, as the short-term costs of digital infrastructure development outweigh the immediate economic benefits. Taken together, the negative long-run elasticity of ICT in the Central Asian context is consistent with a growing body of empirical literature suggesting that ICT's contribution to growth depends critically on complementary conditions-particularly human capital, governance quality, and innovation capacity. In economies where these preconditions are weak, ICT may not directly enhance productivity but could instead impose short-term adjustment costs.

Reverse causality may also play a role. In Central Asia, economic growth constraints such as commodity dependence, limited market integration, and uneven regional development may influence ICT deployment, rather than ICT driving growth. For instance, countries with slower economic expansion may struggle to absorb ICT innovations productively, resulting in a negative association between ICT and measured economic output.

Moreover, the negative coefficient may reflect threshold or non-linear effects specific to the region. ICT's positive impact on productivity may emerge only after a certain level of technological adoption, complementary infrastructure, or institutional capacity is reached. In low- to middle-income Central Asian economies, ICT investments may initially impose costs-such as training, maintenance, or adaptation-without immediate observable gains, producing a temporary negative effect on growth.

Finally, sectoral distribution may be a factor. ICT development in these countries is often concentrated in urban centers or specific sectors (e.g., telecommunications or banking),

limiting broader spillovers to agriculture, manufacturing, or informal sectors that dominate regional economies.

In conclusion, the negative ICT coefficient should be interpreted as conditional and context dependent. It does not imply that ICT is inherently harmful, but rather that its economic contribution in Central Asian countries may be delayed, contingent on institutional quality, complementary human capital, and sectoral absorptive capacity. Future research could explore these mechanisms through dynamic panel models, causal analysis, or subnational studies to capture the complex ICT–growth relationship in this regional context.

The timing of ICT adoption also matters. Countries at earlier stages of digital infrastructure development may experience initial negative or limited growth effects due to adoption costs, skills gaps, and inefficiencies in governance, while the positive effects may emerge later as complementary capacities develop. Moreover, the channels through which ICT affects growth are multifaceted. ICT can directly enhance productivity by optimizing production processes and reducing transaction costs, indirectly stimulate knowledge spillovers and innovation, strengthen human capital through digital skill acquisition, and improve governance by enhancing transparency and administrative efficiency.

These contextual factors suggest that ICT-led growth is not automatic in transitional economies. The effectiveness of ICT depends critically on complementary investments in human capital, institutional quality, and infrastructure. Therefore, the observed negative or limited ICT effects in some Central Asian countries should be interpreted as reflecting regional structural realities rather than contradicting the broader theoretical expectation of ICT-driven growth. These insights highlight the importance of considering country-specific characteristics, institutional readiness, and the timing of digital adoption when assessing ICT's role in economic development.

Therefore, the observed negative relationship should not be interpreted as evidence against ICT-led growth, but rather as an indication that the region has not yet reached the digital development threshold necessary for ICT to act as a sustained engine of economic expansion.

The coefficient of gross capital formation (lngcf) is positive and highly significant across all estimators, with elasticities ranging from 0.80 to 0.92. This implies that a 1% increase in physical capital investment leads to approximately 0.8–0.9% growth in real GDP, confirming the central role of capital accumulation as a driver of economic expansion. This finding aligns closely with the neoclassical growth model, particularly the Solow–Swan framework, which identifies capital deepening as a key mechanism for increasing output per worker. Empirically, similar evidence has been reported for both developing and transition economies. Kuldasheva and Gress (2024) finds that investment remains a major growth determinant in landlocked Central Asian countries, while Rahman et al. (2019) analyzed the determinants of economic growth in South Asian countries using both static and dynamic estimation techniques. Their empirical findings revealed that gross capital formation exerts a positive and significant effect on economic growth, confirming its pivotal role as a key growth driver in the region. Alongside energy consumption and remittances, capital formation was identified as one of the main contributors to GDP growth, although its impact was smaller than that of energy use. The study demonstrated that, as investment in physical capital increases, it strengthens the productive base of South Asian economies, enabling them to achieve higher output levels and improved economic performance. The magnitude of the coefficient in this study is also consistent with results from Haini (2021) and Vu (2011), who emphasize that economies with sustained investment in infrastructure and manufacturing experience stronger productivity gains. In the context of Central Asia, this result underscores the importance of maintaining stable investment flows in physical infrastructure, energy, and industry. Given the region's historical reliance on resource-based

industries, capital accumulation serves not only as a source of production expansion but also as a channel for technological upgrading when directed toward productive sectors. Thus, promoting efficient investment allocation and reducing capital mismanagement are critical to ensuring that capital formation continues to reinforce long-run economic growth.

The coefficient for human capital (lnhc) is positive and statistically significant in the FMOLS and CCR estimations, with elasticities between 0.33 and 0.37, indicating that a 1% increase in human capital contributes to roughly 0.35% higher economic growth. However, the coefficient becomes insignificant in the DOLS model, suggesting some sensitivity to specification. Despite this variation, the overall positive association is consistent with endogenous growth theories (Lucas, 1988; Romer, 1994), which identify human capital as a key driver of technological progress and productivity. Empirical findings widely support the positive contribution of education and skills to economic performance. For example, Hanushek and Woessmann (2012) find that improvements in education quality and attainment significantly enhance growth rates in developing economies. In the context of Central Asia, Kutan and Wyzan (2005) argue that human capital accumulation facilitated structural transformation in Kazakhstan and Kyrgyzstan during the post-Soviet transition, particularly in sectors integrating ICT and advanced technologies.

The results in this study reaffirm that strengthening education systems and fostering digital literacy are crucial for sustaining long-term growth. Moreover, the interaction between human capital and ICT is likely to be complementary: insufficient human capital may partly explain the negative effect of ICT observed earlier. Hence, investment in higher education, technical training, and lifelong learning remains central to enabling technological absorption and innovation in Central Asia.

Trade openness (lntrade) exhibits a positive and significant effect on economic growth in all models, with elasticities ranging between 0.24 and 0.72. This finding suggests that a 1% increase in trade openness is associated with a 0.2–0.7% rise in GDP, implying that integration into international markets fosters economic expansion. These results are consistent with traditional and modern trade theories, such as those of Krugman (1991) and Grossman and Helpman (1991), which posit that openness enhances efficiency through technology transfer, specialization, and competition. Empirical studies provide ample support for this relationship. In Central Asia, Grigoriou (2007) and Felipe and Kumar (2012) similarly report that greater openness, particularly through regional and intercontinental trade corridors, stimulates economic activity by improving resource allocation and access to global markets. However, the magnitude of the elasticity varies across models, which may reflect differences in trade composition across Central Asian economies. Many of these countries remain reliant on primary exports and imported consumer goods. Thus, while trade openness contributes positively to growth, policies that promote export diversification, industrial upgrading, and value-added trade integration are necessary to ensure that openness translates into sustainable economic performance.

Inflation (lninf) demonstrates a negative relationship with economic growth in all models, with coefficients between -0.04 and -0.10, statistically significant in FMOLS and DOLS estimations. This indicates that a 1% increase in inflation reduces economic growth by approximately 0.04–0.10%, reaffirming the classical view that macroeconomic instability hinders productive investment and long-term growth. Empirical evidence consistently supports this inverse relationship. Fischer (1993) find that moderate to high inflation adversely affects growth by creating uncertainty, discouraging savings, and distorting investment decisions. Studies specific to developing regions, such as M. S. Khan and Ssnhadji (2001), identify threshold levels of inflation (typically around 10–12%) beyond which its impact becomes significantly negative. Karahan and Çolak (2020) examined the inflation–growth nexus in Turkey using quarterly data from 2003 to 2017 and employed the Nonlinear Au-

toregressive Distributed Lag (NARDL) model to account for potential asymmetries in the relationship. Their findings revealed a nonlinear negative long-run relationship between inflation and economic growth, providing empirical support for the Classical view that high inflation hampers economic performance. The study concluded that price stability is a fundamental prerequisite for achieving sustainable long-term growth in Turkey. In Central Asia, periods of macroeconomic volatility-particularly following the global financial crisis and commodity price shocks-have been associated with lower investment and slower output expansion. The negative elasticity in this study therefore suggests that maintaining price stability remains critical for sustaining economic growth. Strengthening the credibility and independence of monetary policy, enhancing fiscal discipline, and improving financial market depth can help mitigate the adverse effects of inflation in Central Asian economies.

The coefficient of government effectiveness (govef) is positive and significant in all estimations, with elasticities ranging between 0.33 and 0.43, implying that a 1% improvement in governance effectiveness raises economic growth by about 0.4%. This finding is consistent with institutional growth theory, which emphasizes the role of good governance, rule of law, and administrative capacity in fostering investment and innovation (North, 1990; Acemoglu et al., 2005). Empirical evidence corroborates the positive influence of governance on growth. Kaufmann et al. (2010) show that countries with higher institutional quality achieve faster growth due to reduced corruption and more efficient public resource management. Similarly, Haini (2021) finds that governance quality amplifies the positive impact of ICT and trade openness on growth in developing economies. In the Central Asian context, the variation in government effectiveness, ranging from relatively higher scores in Kazakhstan to lower ones in Tajikistan, partly explains the heterogeneity in growth outcomes across the region. This strong and consistent relationship highlights the necessity of institutional reforms aimed at improving administrative efficiency, transparency, and regulatory quality. Enhanced governance can reduce policy uncertainty, attract foreign investment, and improve the return on ICT and capital investments. Therefore, promoting accountable governance structures is not only a political imperative but also an economic strategy for sustaining long-term development in Central Asia.

The empirical findings of this study provide a mixed confirmation of the proposed hypotheses. The first hypothesis (H1), which posited a positive association between ICT development and economic growth, is rejected, as the results indicate a significant but negative coefficient across all three estimators (FMOLS, DOLS, and CCR). This outcome suggests that ICT penetration in Central Asian economies has not yet translated into productive efficiency and economic expansion, likely due to structural constraints such as weak institutional frameworks, limited absorptive capacity, and uneven digital infrastructure distribution. These findings are consistent with Niebel (2018), who found that the economic benefits of ICT in developing and transitional economies are often delayed or conditional upon human capital and institutional readiness. Conversely, the hypotheses related to gross capital formation (H2), trade openness (H4), and government effectiveness (H6) are strongly supported, affirming the classical and endogenous growth theories that emphasize the roles of investment, trade integration, and institutional quality as essential growth drivers (Kuldasheva & Gress, 2024; Kurmanov et al., 2025). The third hypothesis (H3) concerning human capital is only partially validated, as the variable shows a positive but inconsistent effect across the models, implying that the region's educational systems may not yet be fully aligned with labor market and technological demands. Inflation (H5) exhibited the expected negative relationship, confirming the detrimental impact of macroeconomic instability on long-term growth. Collectively, these results suggest that, while traditional growth drivers (capital formation, trade, and governance) continue to underpin economic expansion in Central Asia, ICT's transformative potential remains underutilized.

Therefore, enhancing the complementarity between ICT, human capital, and governance structures is essential for Central Asian economies to unlock the full productivity benefits of digital transformation.

6. Discussion and Policy Recommendations

The empirical evidence from this study highlights that ICT development alone is insufficient to drive long-term economic growth in Central Asian economies. Policymakers should therefore adopt a comprehensive and integrated strategy that combines digital transformation with complementary structural and institutional measures.

First, human capital development is critical to enhancing the productivity effects of ICT. Education systems should prioritize digital literacy, problem-solving skills, and technological adaptability to strengthen the labor force's absorptive capacity for ICT-driven innovations (Hanushek & Woessmann, 2012; Kutan & Wyzan, 2005). Targeted training programs and vocational education in ICT-intensive sectors can facilitate the translation of digital infrastructure into tangible productivity gains.

Second, governance and institutional quality must be reinforced to maximize the benefits of ICT and other growth-enhancing investments. Improving government effectiveness through regulatory reforms, transparency initiatives, and e-governance mechanisms can enhance policy credibility, reduce corruption, and ensure efficient allocation of resources (Kaufmann et al., 2010; Acemoglu et al., 2005; Haini, 2021). Strong institutions will support the effective application of ICT in public administration, manufacturing, and service sectors, thereby strengthening its contribution to growth.

Third, macroeconomic stability and investment quality are essential for sustaining long-term growth. Containing inflation and directing physical capital formation toward innovation-driven sectors, rather than resource-intensive or low-productivity activities, can improve returns on both digital and physical investments (Salahuddin & Gow, 2016; Kuldasheva & Gress, 2024).

Fourth, trade openness and regional cooperation should be leveraged to facilitate technology diffusion and access to larger markets (Grossman & Helpman, 1994; Krugman, 1991; Baria et al., 2020). Initiatives such as the Belt and Road corridor and digital trade partnerships can enhance connectivity, foster knowledge spillovers, and support diversification toward higher-value goods and services.

Finally, ICT policies should focus on productive applications rather than mere consumption. Investments in digital infrastructure need to be complemented with incentives for innovation, digital entrepreneurship, and industrial adoption, ensuring that digitalization translates into sustainable productivity gains (Salahuddin & Gow, 2016; Niebel, 2018; Vu, 2011; Chavula, 2012; Röller & Waverman, 2001; Baliamoune-Lutz, 2003; Czernich et al., 2011).

By integrating digitalization with human capital enhancement, governance reforms, macroeconomic stability, and investment in productive sectors, Central Asian economies can transition toward a knowledge-based, inclusive, and resilient growth model capable of sustaining long-term prosperity.

7. Conclusions

This study examined whether information and communication technology (ICT) serves as an enduring driver of economic growth in four Central Asian economies (Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan) over the period 2000–2022. By constructing a composite ICT index through Principal Component Analysis (PCA) and employing advanced panel cointegration techniques, namely Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Re-

gression (CCR), the analysis provided robust evidence on the long-running relationship between ICT development and economic performance.

The empirical findings indicate that ICT development exerts a statistically significant but negative impact on economic growth in the long run. This suggests that, despite growing digital infrastructure and ICT penetration, Central Asian economies may not yet be fully equipped to transform digital expansion into sustainable productivity gains. This outcome may reflect structural challenges such as inadequate digital skills, low innovation capacity, inefficient resource allocation, or institutional weaknesses that hinder the effective absorption of ICT benefits. In contrast, gross capital formation, human capital, trade openness, and government effectiveness exhibit strong and positive effects on growth, while inflation exerts a detrimental influence, aligning with theoretical expectations and prior empirical evidence.

From a policy perspective, the findings underscore the need for Central Asian governments to adopt a holistic approach toward digital transformation. Policies should focus not only on expanding ICT infrastructure but also on improving complementary factors such as education, research and development, and institutional quality. Strengthening digital literacy, ensuring affordable broadband access, and fostering a competitive digital market can amplify the growth-enhancing potential of ICT. Furthermore, aligning digital strategies with broader economic diversification goals could enable the region to move from resource dependence toward a more innovation-driven growth path.

Overall, this study contributes to the growing empirical discourse by providing region-specific evidence from Central Asia, an area largely underrepresented in ICT–growth studies. The results highlight that ICT's potential to foster economic growth is contingent on the broader economic and institutional environment. Future research could extend this analysis by incorporating additional institutional indicators, sectoral-level ICT measures, or dynamic panel models to better capture the evolving nature of digital transformation and its long-term economic implications.

A key limitation of this study is the relatively small sample size, consisting of only four Central Asian economies (Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan) over a twenty-three-year period. The limited cross-sectional dimension may reduce the statistical power and reliability of panel-based estimations, including Pedroni, FMOLS, DOLS, and CCR, which are particularly sensitive to small-N panel settings. Although expanding the sample to include additional countries, such as Turkmenistan or other structurally similar economies, could theoretically enhance the robustness of inference, this was not feasible due to substantial data limitations and the lack of consistent long-term macroeconomic and institutional indicators for Turkmenistan. Consequently, the results should be interpreted with caution, as the small number of cross-sectional units may affect the stability of estimated long-run relationships. This limitation is consistent with the broader literature on small-sample panel inference and highlights the potential value of future research employing larger samples, sub-national data, or small-sample-friendly approaches, such as Bayesian or bootstrap-based techniques, to improve statistical reliability.

Another important limitation is the inability to make definitive causal claims due to the absence of advanced endogeneity and causality tests. While the analysis identifies robust associations between ICT, capital, governance, and economic growth, the small sample size and lack of suitable instruments prevent the use of methods such as Granger causality, Dumitrescu–Hurlin tests, or instrumental variable/GMM estimators. As a result, the findings should be interpreted as associations rather than causal relationships. Future research with larger datasets and appropriate instrumental approaches could help address these limitations and provide more conclusive evidence regarding causal linkages.

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