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RESEARCH ARTICLE

Digitalization, Financial Development, and the Growth–Environment Nexus: Evidence from Belt and Road Economies

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Abstract

This study examines the relationships among information and communication technology (ICT) development, financial development, energy consumption, carbon emissions, and economic growth in Belt and Road Initiative (BRI) countries over the period 2000–2019. Employing pooled ordinary least squares (OLS), fixed-effects (FE), generalized least squares (GLS), two-step difference generalized method of moments (GMM), and two-step system GMM estimators, the study investigates the effects of individual ICT indicators and a composite ICT index on economic growth while accounting for financial development, renewable energy consumption, trade openness, and foreign direct investment (FDI). The findings reveal heterogeneous relationships between ICT development and economic growth. Fixed telephone subscriptions and internet usage are predominantly negatively associated with economic growth, whereas fixed broadband subscriptions exhibit a positive association in selected specifications. Financial development produces mixed results depending on the indicators and estimation techniques employed. Similarly, the relationships of energy consumption, renewable energy, and carbon emissions with economic growth vary across models, while FDI consistently exhibits a positive association. The findings underscore the importance of strengthening digital infrastructure, improving financial sector efficiency, and promoting investment in productive and energy-efficient technologies. The study provides policy insights for enhancing digital transformation, financial inclusion, and sustainable economic development across BRI economies.

Keywords: Information and communication technology; Financial development; Economic growth; Carbon emissions; Renewable energy

1. Introduction

The rapid advancement of ICT has transformed economic activities, financial systems, international trade, and industrial production, making digitalization an increasingly important determinant of economic growth (Saba et al., 2025; Mirzaye & Mohiuddin, 2025). ICT facilitates knowledge dissemination, technological innovation, market integration, and resource allocation while reducing transaction costs and improving productivity (Wang et al., 2024a; Meng & Gong, 2024). Digital technologies also enable businesses to access new markets,

strengthen supply chains, and enhance operational efficiency (Raihan, 2024a; Zhen & Shang, 2025). However, the economic benefits of ICT development are not uniformly distributed across countries, as differences in digital infrastructure, institutional quality, financial accessibility, and technological capabilities influence the extent to which digitalization translates into productivity gains (Ayaz & Khattak, 2026). These disparities are particularly relevant for developing and emerging economies, where inadequate infrastructure, limited digital skills, and financial constraints may prevent ICT investments from generating their expected economic benefits (Omer et al., 2026).

Financial development plays a complementary role in facilitating technological advancement and economic growth by mobilizing savings, improving capital allocation, reducing information asymmetries, and financing productive investments (Atsu & Adams, 2023; Yagli & Cetenak, 2023; Daud et al., 2024). Well-developed financial institutions can support ICT infrastructure expansion, technological adoption, and innovation, while digital technologies can enhance financial inclusion, payment efficiency, and access to credit (Li et al., 2024; Aracil et al., 2025; Ha et al., 2025). Nevertheless, the finance–growth relationship remains complex, as excessive credit expansion, inefficient financial intermediation, and the misallocation of financial resources may undermine economic performance (Braun et al., 2024). Consequently, the contribution of financial development to economic growth may depend on the efficiency of financial institutions and their capacity to support productive sectors, including ICT-intensive industries. Examining ICT and financial development jointly is therefore essential for understanding their individual and complementary relationships with economic growth.

The interaction between digitalization, energy consumption, and environmental sustainability adds another dimension to the growth process. Economic expansion generally requires energy for industrial production, transportation, communication infrastructure, and other productive activities. Although ICT can improve energy efficiency through intelligent systems, digital monitoring, and optimized resource management, the expansion of telecommunications networks, data centers, and digital services also increases electricity demand (Wang et al., 2026). Similarly, financial development can facilitate investment in renewable energy technologies and environmentally sustainable infrastructure, potentially supporting economic growth while reducing environmental pressures (Sun et al., 2023; Chen et al., 2024; Khan, 2026). Previous research has demonstrated that ICT, financial development, energy consumption, and carbon emissions are interconnected, although their relationships vary across countries and economic conditions (Weili et al., 2022; Islam et al., 2023; Verma et al., 2023). These considerations highlight the importance of evaluating economic growth alongside energy use and environmental outcomes rather than examining technological and financial development in isolation.

Recent empirical research reinforces the importance of considering these relationships within specific institutional and regional contexts. Amin et al. (2023) examined the connections among ICT, financial development, renewable energy consumption, and environmental sustainability in ASEAN economies, highlighting the importance of their combined effects. Similarly, Rahman and Ferdaous (2024) documented regional differences in the relationships between ICT diffusion, renewable energy consumption, and carbon emissions. Le and Pham (2024) further investigated the environmental implications of financial inclusion and digitalization, while Le et al. (2025) identified potentially contrasting short- and long-run environmental effects of ICT development and financial inclusion. These findings suggest that digitalization and financial development do not necessarily generate uniform economic or environmental outcomes and that their implications depend on structural and institutional conditions.

The Belt and Road Initiative (BRI) provides an important setting for investigating these interrelationships because participating economies differ substantially in their development levels, digital connectivity, financial

systems, energy structures, and integration into international markets. The BRI emphasizes infrastructure connectivity, trade facilitation, investment cooperation, and economic integration, creating opportunities for ICT expansion and financial sector development. However, infrastructure investment and industrial expansion may also increase energy demand and carbon emissions, raising questions about the compatibility of economic growth and environmental sustainability. Recent BRI-focused studies have examined the relationships among ICT, renewable energy, and carbon emissions (Ullah & Li, 2026), the contribution of digital economy development to carbon emission reduction (Wang, 2025), and the role of digitalization and natural resource management in promoting green growth. Collectively, this evidence emphasizes the importance of considering digital and financial development alongside environmental and economic objectives.

Despite these contributions, further investigation is warranted into the joint relationships among ICT development, financial development, energy consumption, carbon emissions, and economic growth in BRI economies. Existing research frequently emphasizes particular dimensions of these relationships, especially the environmental consequences of digitalization or the independent effects of financial development. Comparatively less attention has been devoted to examining multiple ICT indicators alongside alternative measures of financial development within a unified economic growth framework. Furthermore, the potential complementarity between ICT and financial development requires additional empirical assessment, particularly because the economic benefits of digital connectivity may depend on access to financial resources and the efficiency of financial intermediation. Distinguishing between fixed telephone subscriptions, mobile cellular subscriptions, internet usage, and fixed broadband subscriptions is also important, as these technologies differ in their productive applications and economic implications.

Against this background, the present study examines the relationships among ICT development, financial development, energy consumption, carbon emissions, and economic growth in BRI countries during 2000–2019. The analysis employs pooled ordinary least squares (OLS), fixed-effects (FE), generalized least squares (GLS), two-step difference generalized method of moments (GMM), and two-step system GMM estimators. ICT development is measured using four individual indicators and a composite index constructed through principal component analysis, while financial development is represented by alternative financial indicators and a composite financial development index. The study also incorporates interaction terms between ICT and financial development to investigate their combined association with economic growth. Renewable energy consumption, trade openness, and foreign direct investment are included to account for additional economic and structural influences.

The study contributes to the literature by integrating technological, financial, energy, and environmental dimensions within a common empirical framework for BRI economies. Specifically, it distinguishes the relationships of individual ICT technologies with economic growth, evaluates the sensitivity of findings to alternative financial development measures, and examines whether ICT and financial development exhibit complementary associations with economic performance. By comparing static and dynamic panel estimators, the analysis also provides evidence on the consistency and heterogeneity of the estimated relationships. The findings offer policy-relevant insights into strengthening digital infrastructure, improving financial intermediation, encouraging productive investment, and supporting more sustainable economic development across BRI countries.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature and develops the conceptual foundation. Section 3 describes the data, variables, and econometric methodology. Section 4 presents and discusses the empirical findings, while Section 5 concludes the study and outlines its policy implications and directions for future research.

2. Literature review and theoretical framework

2.1. Information and communication technology and economic growth

ICT has emerged as an important determinant of economic growth by facilitating technological innovation, knowledge diffusion, productivity improvements, and market integration. The theoretical relationship between ICT and economic growth can be explained through neoclassical growth theory and endogenous growth theory. The neoclassical growth model emphasizes technological progress as a fundamental driver of long-term economic expansion, whereas endogenous growth perspectives recognize that investment in knowledge, innovation, and technological capabilities can generate sustained productivity improvements. From a Schumpeterian perspective, technological innovation promotes economic transformation by introducing new products, improving production processes, and increasing competitiveness. ICT contributes to these processes by reducing information asymmetries, lowering transaction costs, and improving coordination among economic agents (He et al., 2024; Meng & Gong, 2024).

Empirical evidence generally supports the growth-enhancing potential of ICT, although the magnitude and direction of its effects vary across countries and technologies. Yousefi (2011) demonstrated that the contribution of ICT to economic growth differs between developed and developing economies, suggesting that income levels and technological capabilities influence the realization of digitalization benefits. Similarly, Andrianaivo and Kpodar (2011) identified positive relationships among ICT adoption, financial inclusion, and economic growth in African economies. Salahuddin and Gow (2016) reported that internet usage contributes positively to long-run economic growth in South Africa, while Latif et al. (2018) highlighted the importance of ICT and foreign direct investment in promoting economic performance. Raihan (2023a) further investigated the relationship between information technology and economic growth in India, providing additional country-specific evidence relevant to understanding the economic implications of digitalization in emerging economies. However, Alimi and Adediran (2020) documented mixed relationships between ICT diffusion and economic growth in ECOWAS countries, emphasizing the importance of financial development and regional characteristics. These findings indicate that ICT expansion does not automatically translate into economic growth, particularly where infrastructure limitations, inadequate digital skills, and institutional weaknesses constrain productive technology adoption.

Different ICT indicators may also have distinct economic implications. Fixed broadband connectivity can facilitate high-speed data transmission, digital business activities, and advanced technological applications, whereas mobile cellular subscriptions primarily reflect access to communication services. Internet usage captures broader digital participation, although its economic contribution depends on the intensity and productivity of online activities. Earlier research by Röller and Waverman (2001) and Koutroumpis (2009) demonstrated the economic importance of telecommunications infrastructure and broadband development. Nevertheless, the expansion of digital access may generate limited productivity gains when complementary investments in human capital, infrastructure quality, and institutional capacity are insufficient. Consequently, examining individual ICT indicators alongside a composite ICT index provides a more comprehensive understanding of the relationship between digital development and economic growth.

2.2. Financial development, ICT, and economic growth

Financial development contributes to economic growth by mobilizing savings, facilitating capital accumulation, improving resource allocation, and reducing financing constraints. Efficient financial

institutions support productive investments and technological innovation by improving access to credit and strengthening financial intermediation. Financial development may also complement ICT adoption by providing the resources required for digital infrastructure expansion, technological modernization, and innovation (Kumari & Singh, 2024). Conversely, ICT can improve financial sector efficiency through digital payments, electronic banking, improved information processing, and lower transaction costs. These complementary mechanisms suggest that the economic benefits of ICT may depend partly on the development and efficiency of financial systems (Daud et al., 2024; Oanh, 2024).

Empirical studies provide mixed evidence regarding the finance–growth relationship. Ductor and Grechyna (2015) demonstrated that financial development may negatively affect economic growth when financial expansion exceeds the productive capacity of the real economy. Similarly, Samargandi et al. (2015) identified a nonlinear relationship between financial development and economic growth, indicating that excessive financial deepening may generate diminishing or adverse economic effects. Recent studies have further examined the interrelationships among financial development, economic growth, renewable energy, and environmental sustainability in emerging Asian economies, including Indonesia and Singapore (Raihan et al., 2023; Raihan, 2024b). In contrast, Andrianaivo and Kpodar (2011) found that ICT adoption supports financial inclusion and economic growth, while Alimi and Adediran (2020) emphasized the interconnected roles of ICT diffusion and financial development in shaping economic performance. Raheem et al. (2020) further demonstrated that ICT and financial development exhibit complex relationships with economic growth and carbon emissions. These findings suggest that financial development should not be assessed solely through the expansion of credit or monetary aggregates but also through its capacity to support productive investment and technological advancement.

The interaction between ICT and financial development is particularly important for developing economies, where limited access to financial services and inadequate digital infrastructure may restrict economic opportunities. Digital technologies can expand financial inclusion by reducing geographical barriers and transaction costs, while financial institutions can accelerate digital transformation by financing telecommunications infrastructure and technology-intensive enterprises. However, the effectiveness of these interactions depends on regulatory quality, financial stability, digital literacy, and institutional efficiency. Accordingly, investigating alternative financial development indicators and their interactions with ICT can provide additional insights into the conditions under which digitalization and financial development are associated with stronger economic performance.

2.3. Energy consumption, renewable energy, and economic growth

Energy consumption is an essential component of economic activity because industrial production, transportation, infrastructure development, and technological advancement depend on reliable energy supplies. From a production perspective, energy functions as an important input alongside capital and labor, supporting industrial expansion and economic productivity. However, the growth implications of energy consumption depend on energy efficiency, technological capabilities, and the composition of energy sources. Conventional energy consumption may support economic expansion while simultaneously increasing carbon emissions, whereas renewable energy can contribute to long-term economic resilience by reducing dependence on fossil fuels. Financial development and ICT may further influence these relationships by facilitating investments in energy infrastructure, improving energy management, and supporting the adoption of cleaner technologies.

Existing empirical evidence indicates that the energy–growth relationship is heterogeneous across economies. Shahbaz et al. (2013) emphasized the interconnectedness of energy consumption, financial development, and

economic growth, while Raheem et al. (2020) demonstrated the importance of considering energy and environmental factors alongside ICT and financial development. More recently, Abdullah et al. (2024) examined sustainable economic growth in 20 BRI countries and found that renewable energy consumption and digital finance were positively associated with sustainable growth, whereas energy intensity exhibited a negative relationship. Similarly, Bingxin et al. (2025) investigated the relationship between digitalization and renewable energy development in BRI economies, highlighting the importance of technological progress and human capital in facilitating energy transitions. These findings suggest that the economic implications of energy consumption depend not only on energy availability but also on the efficiency and sustainability of its utilization.

2.4. ICT development, carbon emissions, and environmental sustainability

The relationship between ICT development and carbon emissions is theoretically ambiguous. On the one hand, digital technologies can improve environmental performance through intelligent energy management, efficient transportation systems, digital monitoring, and improved industrial processes (Song et al., 2024; Liu & Wang, 2025). On the other hand, expanding telecommunications infrastructure, digital equipment, and data-processing facilities can increase electricity consumption and associated carbon emissions (Mao et al., 2024; Liu & Wang, 2025). Evidence from Asian economies further illustrates the interconnected roles of ICT, technological innovation, financial development, renewable energy, and economic activity in shaping environmental outcomes (Raihan, 2023b; Raihan & Voumik, 2022; Raihan et al., 2024). The environmental implications of ICT therefore depend on the energy mix, technological efficiency, and scale of digital infrastructure expansion. Furthermore, financial development may either support environmental improvements by financing cleaner technologies or contribute to environmental degradation by encouraging investment in carbon-intensive industries (Liu et al., 2025).

Recent empirical studies provide evidence of these competing mechanisms. Islam et al. (2023) examined ICT, financial development, energy consumption, and carbon emissions in Gulf Cooperation Council economies and found that ICT and financial development were associated with lower emissions, whereas energy consumption increased environmental pressures. Wang et al. (2024b) identified nonlinear relationships between ICT development and carbon emissions, emphasizing the roles of financial development and trade openness. In contrast, Le et al. (2025) found that ICT expansion could increase long-run carbon emissions, although its interaction with financial inclusion generated short-run environmental benefits. These findings demonstrate that the environmental consequences of digitalization are context-dependent and that technological expansion alone does not guarantee environmental sustainability.

Evidence from BRI economies further illustrates the complexity of the ICT–environment relationship. Weili et al. (2022) investigated ICT development, financial development, energy consumption, and carbon emissions in BRI countries and reported that ICT, financial development, and conventional energy consumption were associated with increased emissions, while renewable energy consumption contributed to environmental improvement. More recently, Wang (2025) examined digital economy development and carbon emission reduction across BRI countries, providing additional evidence on the environmental implications of digital transformation. Jafri et al. (2026) also identified heterogeneous relationships among ICT, renewable energy, trade openness, and environmental sustainability in BRI economies. Collectively, these studies suggest that the environmental outcomes of digitalization depend on economic structures, technological capabilities, and energy transitions.

2.5. Trade openness, foreign direct investment, and economic growth

Trade openness and FDI are important determinants of economic growth, particularly in developing and emerging economies seeking greater integration into global markets. International trade facilitates specialization, technological diffusion, and access to intermediate inputs, while FDI can promote capital accumulation, managerial knowledge transfer, and productivity improvements. ICT development may reinforce these benefits by reducing communication costs, facilitating cross-border transactions, and improving coordination within international production networks. Financial development can further strengthen these relationships by providing credit, investment services, and financial infrastructure necessary for international economic activities. Latif et al. (2018) highlighted the interconnected roles of ICT, FDI, globalization, and economic growth, suggesting that digital connectivity and international investment can jointly influence economic performance. Raihan et al. (2025) also examined the roles of renewable energy and foreign direct investment in Egypt's economic growth, offering complementary evidence on the importance of international capital flows and energy transitions for economic performance.

Nevertheless, the effects of trade openness and FDI may differ according to institutional conditions, technological readiness, and industrial structures. Trade expansion and foreign investment can stimulate economic activity but may also increase energy consumption and carbon emissions when production relies heavily on fossil fuels. Butt et al. (2025), examining BRI economies, found that trade openness and energy intensity contributed to environmental pressures, while the environmental implications of technological innovation varied across development conditions. These findings indicate that trade and investment policies should be considered alongside digital development, financial efficiency, and environmental sustainability when evaluating economic growth in BRI countries.

2.6. Research gap and conceptual framework

The reviewed literature establishes that ICT development, financial development, energy consumption, carbon emissions, trade openness, and FDI are interconnected determinants or correlates of economic performance. However, empirical findings remain mixed, particularly regarding the growth implications of individual ICT technologies and alternative financial development indicators. Although recent studies have examined digitalization, financial development, and environmental sustainability in BRI economies, many primarily investigate carbon emissions or renewable energy transitions rather than economic growth as the principal outcome. Furthermore, the extent to which financial development complements ICT in shaping economic growth remains insufficiently established across heterogeneous BRI economies.

The present study addresses these issues by developing an integrated empirical framework in which economic growth is associated with ICT development, financial development, carbon emissions, renewable and conventional energy consumption, trade openness, and FDI. The framework draws on neoclassical and endogenous growth perspectives, financial intermediation theory, and the broader literature on the energy–growth nexus. ICT development is expected to influence economic performance through productivity improvements, technological diffusion, and reduced transaction costs, while financial development may support capital accumulation and technological adoption. Their interaction captures the possibility that access to financial resources conditions the growth benefits of ICT. Energy consumption and carbon emissions reflect the energy-intensive dimensions of economic activity, whereas trade openness and FDI capture international integration and investment-related influences.

By incorporating individual ICT indicators, a composite ICT index, alternative financial development measures, and ICT–finance interaction terms, the study provides a multidimensional assessment of the digitalization–finance–growth relationship. The use of static and dynamic panel estimators further allows the sensitivity of the estimated relationships to alternative econometric specifications to be examined. Accordingly, the study contributes to the literature by clarifying the heterogeneous associations of ICT and financial development with economic growth and providing evidence relevant to economic and digital development policies in BRI countries.

3. Methodology

3.1 Data sources and variable description

This study examines the relationships among ICT, financial development, energy consumption, carbon emissions, and economic growth in BRI countries over the period 2000–2019. The analysis employs annual panel data obtained from the World Development Indicators (WDI) database of the World Bank. The selection of the study period is based on the temporal coverage of the dataset and the availability of relevant economic, financial, technological, and environmental indicators. Economic growth, measured by the annual growth rate of gross domestic product (GDP) per capita, serves as the dependent variable. The explanatory variables include ICT development, financial development, CO_2 emissions, renewable energy consumption, energy consumption, trade openness, and FDI. These variables capture the technological, financial, environmental, and international economic dimensions of growth in BRI economies. The definitions and measurements of the study variables are presented in Table 1.

ICT development is measured using four indicators: fixed telephone subscriptions (FTS), mobile cellular subscriptions (MCS), individuals using the internet (ITU), and fixed broadband subscriptions (FBS). Fixed telephone and mobile cellular subscriptions represent ICT access, whereas internet usage and fixed broadband subscriptions capture ICT utilization. Following Alimi and Adediran (2020), these indicators are incorporated individually to assess their potentially heterogeneous relationships with economic growth. Additionally, a composite ICT development index (ICT-DX) is constructed using principal component analysis (PCA) to capture the broader dimensions of digital connectivity and technological development. PCA reduces the dimensionality of correlated indicators by extracting common variation, thereby providing a composite measure of ICT development.

Financial development is measured using domestic credit to the private sector as a percentage of GDP (FDA), domestic credit to the private sector by banks as a percentage of GDP (FDB), broad money as a percentage of GDP (BM), stock market capitalization as a percentage of GDP (MKT), and the stock market turnover ratio (STRD). These indicators capture different aspects of financial intermediation, liquidity, and capital market development. In addition to examining FDA and FDB separately, a composite financial development index (FD) is constructed using PCA to summarize the information contained in the financial indicators. Employing alternative measures enables the analysis to assess whether the relationship between financial development and economic growth varies across different dimensions of the financial system.

Table 1. Description and Measurement of Variables

Variable	Symbol	Measurement
Economic growth	GDPPC	Annual GDP per capita growth (%)
Fixed telephone subscriptions	FTS	Subscriptions per 100 people
Fixed broadband subscriptions	FBS	Subscriptions per 100 people
Mobile cellular subscriptions	MCS	Subscriptions per 100 people
Internet usage	ITU	Individuals using the internet (% of population)
Domestic credit to private sector	FDA	Percentage of GDP
Domestic credit to private sector by banks	FDB	Percentage of GDP
Broad money	BM	Percentage of GDP
Stock market capitalization	MKT	Percentage of GDP
Stock market turnover ratio	STRD	Turnover ratio of listed domestic shares (%)
Financial development index	FD	Composite financial development index constructed using PCA
ICT development index	ICT-DX	Composite ICT index constructed using PCA
Carbon dioxide emissions	CO_2	Metric tons per capita
Renewable energy consumption	RE	Percentage of total final energy consumption
Energy consumption	EN	Kilograms of oil equivalent per capita
Trade openness	TO	Exports plus imports (% of GDP)
Foreign direct investment	FDI	Net inflows (% of GDP)

The environmental and energy-related variables include CO_2 emissions, measured in metric tons per capita; renewable energy consumption (RE), measured as a percentage of total final energy consumption; and energy consumption (EN), measured in kilograms of oil equivalent per capita. Trade openness (TO) is calculated as the sum of exports and imports relative to GDP, while FDI represents net foreign direct investment inflows as a percentage of GDP. These control variables account for energy dependence, environmental pressures, international economic integration, and foreign capital inflows.

3.2. Model specification

To investigate the relationship between ICT development, financial development, and economic growth, the study specifies a dynamic panel regression model incorporating technological, financial, environmental, and macroeconomic variables. The baseline empirical specification is expressed as follows:

$$GDPPC_{it} = \beta_0 + \beta_1 GDPPC_{i,t-1} + \beta_2 ICT_{it} + \beta_3 FD_{it} + \beta_4 CO2_{it} + \beta_5 RE_{it} + \beta_6 EN_{it} + \beta_7 TO_{it} + \beta_8 FDI_{it} + \varepsilon_{it} \quad (1)$$

where $GDPPC_{it}$ denotes economic growth in country i at time t, and $GDPPC_{i,t-1}$ represents its first lag, capturing the persistence of economic growth. ICT_{it} represents either an individual ICT indicator or the composite ICT development index, while FD_{it} denotes an alternative financial development indicator or the composite financial development index. $CO2_{it}$, RE_{it}, and EN_{it} represent carbon emissions, renewable energy consumption, and energy consumption, respectively. TO_{it} and FDI_{it} capture trade openness and foreign direct

investment. Furthermore, ε_{it} is the idiosyncratic error term, and β_0 and $\beta_1 - \beta_7$ are the parameters to be estimated.

To investigate whether financial development moderates the relationship between ICT development and economic growth, the baseline specification is extended by incorporating an interaction term between the ICT development index and financial development. The extended model is expressed as follows:

$$GDPPC_{it} = \beta_0 + \beta_1 GDPPC_{i,t-1} + \beta_2 ICTDX_{it} + \beta_3 FD_{it} + \beta_4 (ICTDX_{it} \times FD_{it}) + \beta_5 CO2_{it} + \beta_6 RE_{it} + \beta_7 EN_{it} + \beta_8 TO_{it} + \beta_9 FDI_{it} + \varepsilon_{it} \quad (2)$$

Here, $ICTDX_{it} \times FD_{it}$ represents the interaction between ICT development and financial development. The interaction is estimated separately using FDA, FDB, and the composite FD index to assess whether the association between ICT development and economic growth depends on different dimensions of financial development. A positive interaction coefficient would indicate that higher financial development strengthens the marginal association between ICT and economic growth, whereas a negative coefficient would suggest a weakening relationship.

3.3. Econometric estimation techniques

The study employs pooled OLS, fixed-effects (FE), generalized least squares (GLS), two-step difference generalized method of moments (DGMM), and two-step system generalized method of moments (SGMM) estimators to examine the relationships among the study variables. The use of multiple estimation techniques allows the analysis to compare coefficient estimates across alternative specifications and assess their sensitivity to unobserved heterogeneity, dynamic persistence, and potential endogeneity.

Pooled OLS provides an initial assessment of the relationships among the variables but does not adequately account for unobserved country-specific characteristics. The FE estimator addresses time-invariant unobserved heterogeneity by allowing each country to have its own intercept, thereby controlling for persistent differences in institutional structures, geographical characteristics, and other country-specific factors. GLS is employed as an additional estimator to accommodate specified forms of heteroskedasticity and correlation in the regression disturbances. However, these estimators may produce biased or inconsistent estimates when explanatory variables are endogenous. In particular, the inclusion of a lagged dependent variable in a fixed-effects model can generate dynamic panel bias, especially when the time dimension is relatively short.

To address these econometric concerns, the study employs the difference GMM estimator developed by Arellano and Bond (1991). This approach transforms the regression equation through first differencing to eliminate time-invariant country-specific effects and uses appropriately lagged values of endogenous variables as instruments. Difference GMM is particularly useful in dynamic panel models where explanatory variables may be correlated with past or current disturbances. Nevertheless, its performance may deteriorate when variables are highly persistent, as lagged levels can become weak instruments for first-differenced variables.

To improve estimation efficiency, the study additionally applies the system GMM estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998). System GMM combines equations in first differences with equations in levels, using suitable lagged values as instruments under additional moment restrictions. This approach can improve estimation efficiency relative to difference GMM when the relevant assumptions are satisfied. Both difference and system GMM are implemented using two-step estimation procedures, which employ an estimated optimal weighting matrix. The two-step approach can improve

asymptotic efficiency under heteroskedasticity, although appropriate finite-sample corrections to standard errors are important for reliable statistical inference (Roodman, 2009).

3.4. Model diagnostics and robustness assessment

The validity of the dynamic panel estimations is assessed using the Arellano–Bond serial correlation tests and the Sargan test of overidentifying restrictions. The Arellano–Bond procedure examines first-order [AR(1)] and second-order [AR(2)] serial correlation in the first-differenced residuals. First-order serial correlation is generally expected following differencing, whereas the absence of statistically significant second-order serial correlation is an important condition for the validity of the lagged instruments (Arellano & Bond, 1991). The Sargan test evaluates the joint validity of the overidentifying restrictions under its maintained assumptions. A statistically insignificant test result is generally consistent with instrument validity.

The robustness of the empirical findings is further evaluated by comparing estimates obtained from OLS, FE, GLS, DGMM, and SGMM specifications. The analysis considers both individual ICT indicators and the composite ICT index, alongside alternative financial development measures. This approach allows the study to identify whether the estimated relationships are sensitive to variable measurement and model specification. The interaction models additionally provide evidence on the potential complementary relationship between ICT and financial development. Taken together, these estimation strategies provide a comparative framework for evaluating the associations among digitalization, financial development, energy consumption, carbon emissions, and economic growth in BRI economies.

4. Results and discussion

4.1. Descriptive statistics

Table 2 presents the descriptive statistics for the variables included in the empirical analysis. The average annual GDP per capita growth rate is 4.876%, with a standard deviation of 4.616 percentage points, indicating considerable variation in economic performance across the sampled observations. The minimum and maximum growth rates are −33.101% and 54.157%, respectively, reflecting substantial differences in economic conditions and growth trajectories. ICT indicators also exhibit pronounced variation. Fixed telephone subscriptions average 15.544 per 100 people, while fixed broadband and mobile cellular subscriptions average 7.120 and 77.172 per 100 people, respectively. Internet usage averages 30.519% of the population. These differences suggest that mobile connectivity expanded more extensively than fixed broadband infrastructure during the study period, although country-level and temporal differences remain substantial.

Financial development indicators similarly demonstrate considerable heterogeneity. Domestic credit to the private sector averages 44.123% of GDP, while domestic credit provided by banks to the private sector averages 41.540% of GDP. Broad money and stock market capitalization average 58.650% and 47.200% of GDP, respectively, indicating differences in financial depth and capital market development. Regarding environmental and energy indicators, average CO_2 emissions amount to 5.763 metric tons per capita, while renewable energy accounts for 25.896% of total final energy consumption. Average energy consumption is 2561.150 kilograms of oil equivalent per capita. Trade openness averages 94.151% of GDP, and FDI net inflows average 4.273% of GDP. Overall, the descriptive statistics indicate substantial differences in

technological development, financial structures, energy dependence, and international economic integration among BRI economies.

Table 2. Descriptive Statistics

Variable	Mean	Std. deviation	Minimum	Maximum
GDPPC	4.876	4.616	−33.101	54.157
FTS	15.544	12.518	0.018	51.390
FBS	7.120	8.945	0.001	34.984
MCS	77.172	51.512	0.021	212.600
ITU	30.519	28.031	0.011	99.700
FDA	44.123	30.860	0.186	165.390
FDB	41.540	29.538	0.186	165.390
BM	58.650	38.676	7.865	260.060
MKT	47.200	47.200	0.110	303.520
STRD	41.048	59.014	0.121	480.287
CO_2	5.763	8.116	0.037	67.310
RE	25.896	28.301	0.012	95.953
EN	2561.150	3105.846	58.046	22120.370
TO	94.151	52.625	0.167	437.326
FDI	4.273	5.870	−40.410	55.075

4.2. ICT development and economic growth: evidence from static panel models

Table 3 reports the estimated relationships between individual ICT indicators and economic growth using OLS, FE, and GLS estimators, with three alternative financial development measures. Fixed telephone subscriptions exhibit negative and statistically significant coefficients in the OLS and GLS specifications, whereas their coefficients are statistically insignificant in the FE models. This suggests that the negative association is not consistently supported after controlling for time-invariant country characteristics. Fixed broadband subscriptions, by contrast, display positive and significant coefficients in selected specifications, particularly when the composite financial development index is included. The positive coefficient of 0.492 in the OLS and GLS specifications indicates that broadband connectivity is associated with stronger economic growth.

Mobile cellular subscriptions are negatively associated with economic growth in the OLS and GLS models, while the FE estimates are mostly insignificant. Internet usage also exhibits a negative coefficient in selected OLS and GLS specifications, but its statistical significance is not consistent across financial development measures. These findings indicate that different forms of ICT connectivity are associated with different economic outcomes. Broadband infrastructure may offer greater opportunities for productive digital activities, whereas increased telephone and mobile subscriptions do not necessarily translate into productivity improvements. The findings partially contrast with Kumari and Singh (2024), who identified predominantly positive growth effects of ICT infrastructure across low- and high-income economies. Their results nevertheless emphasize that ICT outcomes differ across technologies and development contexts.

Financial development exhibits mixed associations with economic growth. Domestic credit to the private sector (FDA) and bank-provided private credit (FDB) are negatively and significantly associated with growth in the FE specifications, while their OLS and GLS coefficients are generally insignificant. The composite financial development index exhibits positive and significant coefficients in OLS and GLS but negative coefficients in FE. This divergence suggests that cross-country differences and within-country changes in financial development may capture distinct economic relationships. The findings are broadly consistent with Ductor and Grechyna (2015) and Samargandi et al. (2015), who emphasized that financial deepening does not necessarily generate uniform growth benefits.

Table 3. ICT indicators and economic growth: OLS, FE, and GLS estimates (coefficients are reported in the order FDA / FDB / FD within each estimator)

Variable	OLS			FE			GLS		
	FDA	FDB	FD	FDA	FDB	FD	FDA	FDB	FD
FTS	−0.58**	−0.44*	−0.63**	0.57	0.23	0.32	−0.58**	−0.44*	−0.63**
FBS	0.13	−0.08	0.49**	0.34*	−0.03	0.16	0.14	−0.08	0.49**
MCS	−0.70**	−0.70**	−1.65***	−1.23**	−0.30	−0.86	−0.70**	−0.70**	−1.65***
ITU	−0.68**	−0.45	−0.69	0.09	−0.31	0.19	−0.68**	−0.45	−0.69
FDA	0.01	—	—	−0.09***	—	—	0.01	—	—
FDB	—	−0.00	—	—	−0.09***	—	—	−0.00	—
FD index	—	—	0.89***	—	—	−4.75***	—	—	0.89***
CO_2	0.28***	0.25***	0.34***	0.19	0.13	0.33*	0.28***	0.25***	0.34***
RE	0.01	0.00	0.04***	−0.21***	−0.15***	−0.23**	0.01	0.00	0.04***
EN	−0.00	−0.00	−0.00	−0.00	−0.00	0.00	−0.00	−0.00	−0.00
TO	0.00	0.00	−0.00	0.05***	0.05***	0.03**	0.00	0.00	−0.00
FDI	0.89***	1.19***	0.90***	1.03***	1.19***	1.09***	0.80***	1.19***	0.90***
N	571	670	293	571	670	293	571	670	293

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively

Regarding the control variables, CO_2 emissions are positively associated with economic growth in most OLS and GLS specifications, potentially reflecting the energy-intensive nature of production and industrial expansion. Renewable energy consumption exhibits positive coefficients in selected OLS and GLS models but negative coefficients in the FE specifications. Trade openness is positively associated with growth in the FE models, while FDI consistently exhibits positive and statistically significant coefficients across the reported specifications. These findings underscore the importance of international investment and economic integration in the sampled economies.

4.3. Dynamic panel estimates of individual ICT indicators

Table 4 presents the DGMM and SGMM estimates for individual ICT indicators and financial development measures. The results demonstrate considerable variation across estimation methods. Fixed telephone subscriptions exhibit a positive and significant coefficient in the DGMM specification incorporating FDA but negative and significant coefficients in two SGMM specifications. Fixed broadband subscriptions are negatively associated with growth in the DGMM model incorporating FDB, whereas the SGMM model using the composite FD index produces a positive and significant coefficient of 0.794. These findings provide qualified support for the potential growth benefits of broadband connectivity but do not establish a uniformly positive relationship across all financial development measures.

Mobile cellular subscriptions display a negative and significant coefficient in one DGMM specification, whereas their SGMM coefficients are statistically insignificant. Internet usage exhibits positive and significant coefficients in two DGMM specifications but negative and significant coefficients across all three SGMM models. The contrasting results indicate sensitivity to the estimation strategy and underlying identifying assumptions. Although the negative SGMM estimates suggest that expanded internet access was not consistently associated with stronger economic growth, this finding should not be interpreted as evidence that internet adoption inherently reduces productivity. Digital infrastructure quality, productive utilization, digital literacy, and financial accessibility may help explain the heterogeneous relationships. Recent evidence from Ayaz and Khattak (2026) similarly identifies differences in the economic benefits of digitalization between developed and developing economies, including a negative growth relationship for the latter.

Table 4. ICT indicators and economic growth: difference and system GMM estimates

Variable	DGMM			SGMM		
	FDA	FDB	FD	FDA	FDB	FD
FTS	2.252**	−0.432	0.762	−1.961**	−0.683	−4.169*
FBS	0.290	−0.682***	0.073	−0.098	−0.039	0.794**
MCS	−3.158***	−0.691	0.114	0.129	−0.159	0.697
ITU	1.604***	1.445**	−1.252	−0.857**	−0.860*	−4.329*
FDA	−0.061***	—	—	−0.010	—	—
FDB	—	−0.432	—	—	0.203*	—
FD index	—	—	−1.892	—	—	−2.290
CO_2	0.253**	−0.682***	0.278	0.147	−0.079	−0.012
RE	−0.193***	−0.691	−0.280	−0.073	−0.000	−0.147
EN	−0.000***	1.445**	0.001	0.000	0.009	0.001
TO	0.098***	−0.115***	0.049**	0.014	1.300***	−0.016
FDI	1.343***	0.078	0.944***	1.210***	0.197***	0.632**
Lagged GDPPC	−0.026	−0.211***	0.009	0.141***	9.504**	0.201***
Observations	493	581	246	566	664	290
Countries	57	60	33	58	61	33
AR(1) p-value	0.001	0.001	0.003	0.001	0.001	0.007
AR(2) p-value	0.240	0.470	0.030	0.558	0.470	0.116
Sargan p-value	0.001	0.010	0.030	0.003	0.001	0.036

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively

The financial development estimates also vary across specifications. FDA exhibits a negative and significant coefficient in one DGMM model but an insignificant coefficient in SGMM. FDB is positively associated with growth in one SGMM specification, whereas the composite FD index is insignificant in both sets of models. CO_2 emissions are statistically significant in selected DGMM specifications but insignificant across the SGMM models. Renewable energy consumption and conventional energy use also exhibit mixed results. FDI remains positively associated with economic growth in all SGMM specifications, reinforcing the positive relationship identified in the static panel estimates.

4.4. Composite ICT development index and economic growth

To assess whether the findings are sensitive to the measurement of ICT development, the analysis employs a composite ICT index constructed using principal component analysis. Table 5 presents the OLS, FE, and GLS estimates incorporating this index. The ICT index exhibits negative and statistically significant coefficients across all OLS and GLS specifications, ranging from −1.455 to −0.991. The FE estimates are also negative and significant when FDA or FDB is included, although the coefficient becomes insignificant when the composite FD index is employed. These results suggest that the overall expansion of ICT infrastructure and usage was not consistently associated with higher economic growth during the study period.

The negative ICT–growth relationship contrasts with conventional expectations that technological development necessarily promotes productivity and economic expansion. However, it is consistent with the possibility that ICT investment requires complementary improvements in digital skills, institutional capacity, financial accessibility, and productive technological applications before its economic benefits are fully realized. Kumari and Singh (2024) reported differences in the joint contributions of ICT infrastructure, financial development, and trade openness across income groups, while Li et al. (2024) found that the relationship between ICT diffusion and financial development varies according to national income levels. These findings reinforce the importance of economic and institutional conditions in shaping the benefits of digitalization.

The estimated relationships between financial development and economic growth remain heterogeneous. FDA is negative and significant in the FE model but insignificant in OLS and GLS. FDB exhibits negative coefficients across the estimators, although their magnitudes and significance vary. The composite FD index is positively associated with growth in OLS and GLS but negatively associated with growth in FE. CO_2 emissions generally exhibit positive coefficients, while renewable energy consumption is positively associated with growth in OLS and GLS and negatively associated with growth in FE. Trade openness is positively associated with economic growth in several specifications, and FDI consistently exhibits positive and significant coefficients.

Table 5. Composite ICT index and economic growth: OLS, FE, and GLS Estimates

Variable	OLS			FE			GLS		
	FDA	FDB	FD	FDA	FDB	FD	FDA	FDB	FD
ICT index	−1.28***	−1.45***	−0.99***	−0.62**	−1.03***	−0.22	−1.28***	−1.46***	−0.99***
FDA	0.00	—	—	−0.07***	—	—	0.00	—	—
FDB	—	−0.01*	—	—	−0.08***	—	—	−0.01*	—
FD index	—	—	0.78***	—	—	−4.08***	—	—	0.78***
CO_2	0.31***	0.29***	0.29**	0.19*	0.16	0.32*	0.31***	0.29***	0.29**
RE	0.04***	0.03***	0.06***	−0.16***	−0.09*	−0.24**	0.04***	0.03***	0.06***
EN	−0.00**	−0.00**	−0.00	−0.00	−0.00	0.00	−0.00**	−0.00**	−0.00
TO	0.01**	0.01**	0.00	0.06***	0.06***	0.04***	0.01**	0.01**	0.00
FDI	0.70***	0.96***	0.71***	0.88***	1.01***	1.12***	0.70***	0.96***	0.71***
N	576	675	298	576	675	298	576	675	298
R^2	0.17	0.17	0.18	0.18	0.20	0.25	—	—	—
Countries	58	61	33	58	61	33	58	61	33

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively

Table 6 reports the corresponding dynamic panel estimates for the composite ICT index.

Table 6. Composite ICT index and economic growth: difference and system GMM estimates

Variable	DGMM			SGMM		
	FDA	FDB	FD	FDA	FDB	FD
ICT index	−0.668**	−0.712***	−0.678	−1.287***	−1.215***	−0.361
FDA	−0.085***	—	—	−0.016	—	—
FDB	—	−0.133***	—	—	−0.042*	—
FD index	—	—	−2.133*	—	—	−1.023
CO_2	0.140	0.245*	0.340**	0.184**	0.093	−0.070
RE	−0.210***	−0.166***	−0.186	−0.018	−0.038	0.065
EN	−0.000**	0.000**	0.000	−0.000	−0.000	0.001*
TO	0.105***	0.079***	0.050***	0.019**	0.011	−0.013
FDI	1.077***	1.410***	1.079***	0.788***	0.879***	0.866***
Lagged GDPPC	−0.069***	0.006	0.021	0.135***	0.217***	0.272***
Observations	498	586	251	571	669	295
Countries	57	60	33	58	61	33
AR(1) p-value	0.001	0.001	0.004	0.001	0.010	0.001
AR(2) p-value	0.153	0.068	0.018	0.510	0.482	0.066
Sargan p-value	0.001	0.010	0.001	0.002	0.010	0.045

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively

The DGMM results show negative and statistically significant coefficients when FDA and FDB are included, whereas the coefficient becomes insignificant when the composite FD index is employed. Similarly, the SGMM estimates are negative and significant in the FDA and FDB specifications but insignificant in the composite FD specification. These findings provide additional evidence of a negative conditional association between ICT development and economic growth in selected models.

Financial development also displays heterogeneous results in the dynamic specifications. FDA and FDB are negatively associated with growth in DGMM, whereas FDA becomes insignificant and FDB remains weakly negative in SGMM. The composite FD index is negative and weakly significant in DGMM but insignificant in SGMM. CO_2 emissions exhibit positive coefficients in selected DGMM and SGMM specifications, while renewable energy consumption is negatively associated with growth in two DGMM models but insignificant across SGMM specifications. FDI consistently exhibits positive and statistically significant coefficients in both estimators.

4.5. Interaction between ICT and financial development

Table 7 consolidates the main findings and reports interaction terms between the composite ICT index and alternative financial development indicators. The DGMM estimates indicate positive and statistically significant interactions between ICT and FDA (0.0107) and between ICT and FDB (0.0341). These results suggest that financial development may strengthen the conditional relationship between ICT development and economic growth, potentially offsetting part of the negative association observed for the ICT index. However, the corresponding SGMM interaction coefficients are positive but statistically insignificant. The interaction between ICT and the composite FD index is also insignificant in both dynamic estimators.

Table 7. ICT–financial development interactions: comparative GMM estimates

Variable	DGMM			SGMM		
	FDA	FDB	FD	FDA	FDB	FD
ICT index	−0.668**	−0.712***	−0.678	−1.287***	−1.215***	−0.361
FDA	−0.085***	—	—	−0.016	—	—
FDB	—	−0.133***	—	—	−0.042*	—
FD index	—	—	−2.133*	—	—	−1.023
FDA × ICT	0.0107**	—	—	0.00167	—	—
FDB × ICT	—	0.0341***	—	—	0.00667	—
FD × ICT	—	—	1.002	—	—	0.447
Observations	498	586	251	571	669	295
Countries	57	60	33	58	61	33

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively

These findings provide limited and estimator-dependent evidence of complementarity between ICT and financial development. The positive DGMM interactions are consistent with the theoretical argument that access to financial resources can facilitate productive ICT adoption, technological investment, and digital innovation. However, the lack of statistical significance in SGMM prevents a firm conclusion that financial development systematically moderates the ICT–growth relationship. Kumari and Singh (2024) similarly emphasized the complementary role of financial development in the economic contribution of ICT infrastructure, while Li et al. (2024) highlighted differences in the ICT–finance relationship across income groups. More recent evidence from Pal and Villanthenkodath (2026) also supports the relevance of digitalization and institutional conditions for financial development in emerging Asian economies.

4.6. Discussion of the findings

The empirical findings highlight the importance of distinguishing between digital connectivity and the productive utilization of digital technologies. The positive association between fixed broadband subscriptions and economic growth in selected specifications suggests that reliable, high-capacity digital infrastructure may be particularly relevant for supporting business productivity, digital services, and technological innovation. Conversely, the negative associations observed for several ICT indicators and the composite ICT index suggest that improvements in digital access alone may be insufficient to generate immediate economic benefits. These findings support the argument that digital transformation requires complementary investments in human capital, institutional quality, financial accessibility, and technological capabilities. The broader interactions among digitalization, technological innovation, and financial accessibility have also been examined in advanced economies, highlighting the relevance of complementary technological and financial conditions for environmental sustainability (Raihan et al., 2026). Recent evidence from Kumari and Singh (2024) and Ayaz and Khattak (2026) similarly highlights the heterogeneous economic outcomes of digitalization across countries with different development characteristics.

The mixed financial development results further suggest that expanding credit availability or financial market size does not necessarily translate into stronger economic performance. The effectiveness of financial development may depend on whether financial resources support productive investment, technological innovation, and business development. The positive ICT–finance interactions observed in selected DGMM specifications are consistent with this interpretation, although their statistical insignificance in SGMM limits

the strength of the conclusion. These findings suggest that financial sector policies should emphasize efficient credit allocation, digital financial services, and investment in productive ICT infrastructure rather than financial expansion alone.

The relationships involving carbon emissions and energy consumption also have important implications for sustainable development. The positive association between CO_2 emissions and economic growth in several specifications may reflect the dependence of some BRI economies on energy-intensive industrial production. However, this relationship should not be interpreted as evidence that higher emissions promote economic growth. Instead, it may reflect common underlying drivers, including industrialization, fossil fuel consumption, and infrastructure expansion. Recent evidence from Islam et al. (2023) demonstrates the complex interactions among ICT, financial development, energy use, and emissions, while Butt et al. (2025) highlight the environmental challenges associated with trade expansion and energy intensity in BRI economies.

The mixed estimates for renewable energy consumption suggest that the economic implications of energy transitions may depend on investment requirements, technological maturity, infrastructure readiness, and institutional conditions. Accordingly, policies aimed at expanding renewable energy should be accompanied by investments in grid modernization, technological innovation, and financial mechanisms that facilitate the adoption of cleaner energy technologies. The consistently positive association between FDI and economic growth further suggests that international investment can support economic activity in BRI economies. Nevertheless, investment policies should prioritize technological upgrading, knowledge transfer, and environmentally sustainable production to improve the quality and durability of economic growth (Raihan & Sarkar, 2026).

Overall, the findings suggest that the economic benefits of ICT development are conditional on broader financial, technological, and institutional circumstances. Strengthening broadband infrastructure, improving financial intermediation, encouraging productive foreign investment, and supporting cleaner energy systems may help BRI economies realize more inclusive and sustainable economic development. However, given the identified GMM diagnostic concerns, these policy implications should be regarded as provisional and grounded in observed associations rather than established causal effects.

5. Conclusions and policy implications

5.1. Conclusions

This study investigates the relationships among ICT development, financial development, energy consumption, CO_2 emissions, and economic growth in BRI countries over the period 2000–2019. Employing pooled OLS, FE, GLS, two-step DGMM, and two-step system GMM (SGMM) estimators, the study provides empirical evidence on the heterogeneous associations of digitalization and financial development with economic performance. By incorporating individual ICT indicators, a composite ICT index, and alternative financial development measures, the analysis contributes to understanding the technological, financial, and environmental dimensions of economic growth in BRI economies.

The findings reveal that the relationship between ICT development and economic growth varies across technologies and econometric specifications. Fixed telephone subscriptions and internet usage generally exhibit negative associations with economic growth in selected models, whereas fixed broadband subscriptions demonstrate positive and statistically significant relationships in some specifications. The composite ICT index is also negatively associated with economic growth in several models, suggesting that the expansion of digital connectivity does not necessarily translate into immediate economic benefits. Financial development produces

mixed results depending on the indicators and estimation techniques employed, highlighting the importance of financial sector efficiency and productive resource allocation. Although the interaction between ICT and financial development is positive and statistically significant in selected DGMM specifications, the corresponding SGMM estimates are insignificant, providing limited evidence of a robust complementary relationship. Furthermore, CO_2 emissions and energy consumption exhibit heterogeneous relationships with economic growth, while renewable energy consumption produces mixed results. In contrast, foreign direct investment consistently demonstrates a positive and statistically significant association with economic growth across most specifications. Overall, the findings suggest that the economic benefits of digitalization depend on complementary financial, technological, and structural conditions rather than ICT expansion alone.

5.2. Policy implications

The findings offer several policy implications for promoting economic growth and sustainable development in BRI economies. First, policymakers should prioritize the development of reliable and affordable broadband infrastructure while improving digital literacy, technological capabilities, and the productive utilization of ICT. The positive association between fixed broadband subscriptions and economic growth in selected specifications suggests that high-quality digital connectivity may be particularly important for enhancing business productivity, innovation, and market integration. Second, financial sector reforms should emphasize efficient credit allocation, financial inclusion, and improved access to financing for technology-intensive enterprises. Strengthening cooperation between financial institutions and the ICT sector may facilitate digital transformation and improve the economic returns on technological investment. Third, governments should encourage foreign direct investment and international trade through transparent regulatory frameworks, investment-friendly institutions, and policies that promote technological upgrading and knowledge transfer. Finally, the mixed relationships involving energy consumption, renewable energy, and carbon emissions highlight the need to integrate economic development strategies with environmental sustainability objectives. Investment in renewable energy infrastructure, energy-efficient technologies, and green financing mechanisms could help BRI economies pursue economic growth while reducing their dependence on carbon-intensive production systems.

5.3. Limitations and future research directions

Despite its contributions, this study has several limitations that provide opportunities for future research. First, the analysis covers 2000–2019 and therefore does not capture more recent developments in digital transformation, financial technology, renewable energy investment, and economic restructuring. Second, the study relies on aggregate country-level indicators that may not fully reflect differences in ICT quality, digital skills, financial inclusion, and institutional effectiveness. Third, the considerable heterogeneity among BRI economies suggests that the estimated relationships may differ across income groups, geographical regions, and stages of technological development. Future studies should extend the sample period, incorporate measures of institutional quality and digital readiness, and investigate potential nonlinearities, threshold effects, and regional heterogeneity. Further research could also employ alternative estimation strategies and improved instrument specifications to strengthen the reliability of empirical findings. Such extensions would provide a more comprehensive understanding of how digitalization, financial development, and energy transitions can jointly support inclusive and environmentally sustainable economic growth in BRI countries.

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