DOI: 10.55643/fcaptp.1.66.2026.4979

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Received: 28/08/2025
Accepted: 30/01/2026
Published: 28/02/2026

THE IMPACT OF DIGITAL AND GREEN TRANSFORMATION ON SUSTAINABLE ECONOMIC GROWTH: EMPIRICAL EVIDENCE FROM VIETNAM

ABSTRACT

The dual transition toward digitalisation and green development has become a strategic priority for emerging economies seeking sustainable growth. However, empirical evidence on the simultaneous financial transmission mechanisms of these two transformations remains limited. This study explores the short- and long-term implications of the impact of digital transformation and green transformation on Vietnam's sustainable economic development in the period 1995–2023, with a particular focus on the financial factors supporting the twin-transition agenda. Using annual macro-financial time-series data and the Autoregressive Distributed Lag (ARDL) model, complemented by the Bayer–Hanck cointegration test, the analysis integrates key indicators of digitalization (EGDI and Internet usage), green transformation (renewable energy share and the SDG Index), and financial variables including public investment, domestic credit to the private sector, and green foreign direct investment, with trade openness capturing global integration. The results confirm the existence of a stable long-run cointegrating relationship, indicating that digitalization and green transformation exert positive and statistically significant effects on sustainable economic growth. Financial factors play a catalytic role: private sector credit averaged over 90% of GDP since 2015 and reached 128.68% in 2023, facilitating the diffusion of digital technologies and supporting renewable energy projects, while public investment (approximately 7% of GDP) accelerates the upgrading of green and digital infrastructure. In contrast, green FDI inflows remain modest, highlighting untapped potential for ESG-oriented capital. The findings underscore the need for coordinated financial and fiscal frameworks to expand green financial instruments, enhance the efficiency of green and digital public investment, attract high-quality green FDI, and align financial markets with sustainability objectives. This study contributes novel finance-based empirical evidence for Vietnam and provides insights relevant to other emerging economies pursuing finance-driven digital and green transformation for sustainable development.

Keywords: digital transformation, green transformation, sustainable economic growth, green finance, public investment, domestic credit, green FDI, ARDL model, Vietnam

JEL Classification: C32, O33, Q01, Q56

INTRODUCTION

Sustainable economic growth has emerged as a central policy objective for both advanced and emerging economies in the context of deepening globalization, accelerating climate change, and increasing pressure on natural resources. Beyond the traditional growth paradigm based on capital accumulation and labor expansion, contemporary development strategies increasingly emphasize structural transformation toward a digitalized and environmentally sustainable economy (UN, 2015; OECD, 2020). In this context, digital transformation and green transformation are widely regarded as two interrelated pillars that reshape production structures, enhance productivity, and redefine long-term growth trajectories.

Digital transformation is a core pillar of sustainable economic development, reflecting the economy-wide integration of digital technologies into production, market exchange,

and public administration. Among digitalization indicators, the E-Government Development Index (EGDI) plays a particularly important role, as it captures the quality of digital public services, online service delivery, and institutional readiness for digital governance. By enhancing transparency, reducing administrative and transaction costs, and improving coordination between the public and private sectors, higher EGDI levels facilitate productivity gains and strengthen national competitiveness. Empirical evidence consistently shows that improvements in EGDI, alongside expanded ICT infrastructure and Internet access, are associated with higher GDP growth and labor productivity, especially in developing and transition economies (Bukht & Heeks, 2018; Vu, 2017; Majeed & Ayub, 2018; World Bank, 2022).

Complementing digitalization, green transformation represents a parallel and equally critical pathway toward sustainable economic growth by aligning production and consumption patterns with environmental constraints. This transformation emphasizes the reduction of carbon intensity, the large-scale deployment of renewable energy, and the adoption of environmentally friendly technologies to decouple economic growth from ecological degradation. Beyond environmental benefits, the transition toward clean energy and green technologies generates new investment opportunities, stimulates innovation, and supports the creation of high-quality employment, thereby enhancing macroeconomic resilience. Empirical studies consistently suggest that green transformation contributes to long-term growth sustainability by improving energy efficiency, mitigating climate-related risks, and fostering a more stable and diversified economic structure (Stern, 2006; OECD, 2011; Zhang et al., 2017; Shahbaz et al., 2023).

In Vietnam, the government has actively advanced digital transformation and green transformation through national development strategies, including the National Digital Transformation Strategy for the period 2025 to 2030 and the National Green Growth Strategy for 2021 to 2030. Despite these strong policy initiatives, empirical evidence on the combined effects of digital and green transformation on economic growth in Vietnam remains limited. This gap is particularly evident in a developing economy context, where financial channels, public investment, and private credit are central to transmitting the impacts of structural transformation to growth outcomes.

To address this gap, this study examines the short-run and long-run effects of digital transformation, green transformation, and financial factors on sustainable economic growth in Vietnam over the period from 1995 to 2023. By explicitly incorporating financial transmission mechanisms into the empirical framework, the study offers new insights into the interconnected roles of digitalization, environmental transition, and finance in fostering sustainable growth in a developing economy such as Vietnam.

LITERATURE REVIEW

Theoretical framework

Sustainable economic growth is defined as a development process that combines the three core pillars: Economic development, social enhancement, and environmental protection; this process aims at long-term economic growth accompanied by equity and natural resource preservation (UNDP, 2015; Sachs et al., 2021). According to Sachs et al. (2016), economic growth can be considered truly sustainable only when three conditions are simultaneously achieved: poverty reduction, enhanced social equity, and effective control of environmentally damaging factors.

Digital transformation is defined as the process of integrating digital technologies into all sectors of the economy, thus altering traditional modes of production and business while creating new value based on data, connectivity, and automation (Bukht & Heeks, 2017). From a theoretical perspective, digital transformation enhances total factor productivity (TFP), resource allocation, and innovation (Lucas, 1988; Romer, 1990; Jones, 1995). In addition, digital transformation strengthens the effectiveness of public governance through e-government and public service digitalization, thereby enhancing transparency and reducing administrative costs (Choi et al., 2022).

Green transformation denotes a shift in economic development toward environmentally sustainable pathways, characterized by the mitigation of greenhouse gas emissions, the expansion of renewable energy use, and the advancement of green technological innovation (Stern, 2006; UNEP, 2012). From the perspective of endogenous growth theory, such a transition supports long-term economic growth by enhancing resource efficiency and innovation capacity, while simultaneously reducing environmental risks and ecological pressures (Romer, 1990; Sachs et al., 2016).

Both digital transformation and green transformation are regarded as two key driving forces of sustainable development in the 21st century, as these factors exert profound influences on economic growth through three primary channels: the capital accumulation channel, the productivity channel, and the financial channel. These channels of digital transformation and green transformation are explained as follows.

First, the investment channel: Digital transformation stimulates investment in digital infrastructure, information technology, big data, and high-skilled human capital; green transformation encourages investment in renewable energy, energy efficiency technologies, and clean production. Together, these investments enhance capital accumulation and improve resource efficiency (Acemoglu et al., 2012; Jorgenson & Vu, 2016; Su et al., 2013).

Second, the productivity channel: Digital and green technologies enhance total factor productivity through innovation, automation, and optimal resource allocation. Brynjolfsson and Hitt (2000) as well as Salahuddin and Alam (2016) argue that the adoption of information technology reduces transaction costs, expands market scale, and promotes economic efficiency.

Third, the financial channel: The effects of digital and green transformation depend on the level of financial development, the capacity to mobilize public investment, and public debt status. Public investment plays a catalytic role in facilitating private investment and green finance, whereas high public debt may constrain fiscal space and hinder investment efficiency (Levine, 2005; Égert & Gal, 2017).

Moreover, due to the inherently long-term nature of digital and green transformations, their impact on economic growth is heterogeneous over time and may differ between short-term adjustments and long-term outcomes. To capture and differentiate these dynamic effects, this study applies the theoretical framework Autoregressive Distributed Lag (ARDL) developed by Pesaran, Shin, and Smith (2001), which allows for accurate estimation of both short-term responses and long-term equilibrium relationships. Additionally, factors such as trade openness, digital infrastructure development, internet usage rates, and the Sustainable Development Goals (SDG) Index are incorporated into the model as control variables. These variables reflect the economy's integration status and access to technology, and environmental commitment (Rodrik, 2006; OECD, 2017; Sachs et al., 2021).

In summary, the analysis of how digital transformation and green transformation shape sustainable economic growth must rest on well-established theoretical foundations drawn from endogenous growth theory, innovation theory, and the sustainable development paradigm. These theoretical perspectives clarify the channels through which digitalization and greening affect economic performance in both the short and long run, while also providing a coherent rationale for variable selection, empirical model specification, and the interpretation of results in a manner that reflects Vietnam's specific economic conditions.

Review of Empirical Studies

The economic development literature has extensively examined the relationship between digital transformation, green transformation, and sustainable economic growth. With respect to digital transformation, Azman Saini et al. (2010) and Zhang et al. (2017) highlight the importance of technological progress and digital infrastructure in improving labor productivity, production efficiency, and overall economic performance. Empirical studies by Vu (2017), Vu et al. (2023), and Pham et al. (2022) further demonstrate that advances in digital technologies, especially in information and communication infrastructure and electronic commerce, play a significant role in promoting firm-level innovation, strengthening business performance, and facilitating modern economic restructuring. In a similar vein, Niebel (2018), Vu (2017), Katz and Koutroumpis (2013), and Su et al. (2013) provide evidence that increased investment in digital infrastructure and e-government systems enhances total factor productivity and supports long-term economic growth by improving the efficiency of resource allocation and fostering innovative capacity.

The literature has consistently illustrated that green transformation plays a critical role in promoting environmentally sustainable economic growth. Stern (2006), Sachs et al. (2016, 2021), and UNEP (2012) highlight the importance of environmental policies, investments in clean technologies, and renewable energy in shaping and implementing environmentally friendly growth models. Various empirical studies, such as Apergis and Payne (2010), Shahbaz et al. (2017), Busu and Trica (2019), and Radivojević et al. (2024), show that renewable energy and green investment have positive long-run effects on GDP growth, resource usage efficiency, and emission reduction. In addition, Alola et al. (2022) and Shahbaz et al. (2023) find that improvements in the Sustainable Development Goals (SDG) Index and reductions in greenhouse gas emissions contribute to higher growth quality and greater economic resilience.

In addition to the digital and green transformation, the literature has emphasized the roles of financial transmission channels in transmitting the effect between digital transformation and green transformation on sustainable economic growth. Levine (2005), Beck et al. (2000), Égert and Gal (2017), Majeed and Ayub (2018), and Murshed et al. (2022) emphasize that public investment, private credit, and foreign direct investment (FDI) play a crucial intermediary role in transmitting the effects of digital and green transformation policies to economic growth. These studies suggest that finance is not

DOI: 10.55643/fcaptp.1.66.2026.4979

merely a supporting investment tool, but also a decisive factor in determining the economy's capacity to absorb new technologies and foster innovation.

In Vietnam, various studies, such as Le and Hoang (2021), Nguyen and Bui (2022), and Breisinger et al. (2011), have examined the roles of economic structure, public investment, and technological innovation in promoting inclusive growth. However, these studies tend to focus on these factors individually, either digital transformation or green transformation, rather than considering them simultaneously; additionally, they have not fully assessed long-term impacts from a sustainable development perspective.

Overall, the international and domestic studies reveal a significant research gap in the simultaneous effects of digital transformation and green transformation on sustainable economic growth, particularly in Vietnam as a developing economy. Most existing studies either examine the individual impacts of each factor or fail to consider the mediating role of the financial systems. Therefore, this study extends the existing empirical literature by constructing a quantitative model that incorporates groups of variables representing digital transformation (e-government development index, Internet usage rate, trade openness), green transformation (renewable energy usage, green investment, Sustainable Development Index), and financial channels (public investment, private credit, green FDI), in order to assess the short-run and long-run impacts of these factors on sustainable economic growth in Vietnam from 1995 to 2023.

Research Gaps and Contributions

Although international studies have extensively analyzed the relationship between digital transformation, green transformation, and economic growth, most have not examined these two processes simultaneously within a single baseline regression, nor have they adequately analyzed the mediating role of public finance and private credit in developing economies. This study makes three main contributions:

1. Firstly, both digital and green transformation processes are incorporated into a unified dynamic growth model, reflecting the realities of contemporary sustainable development.
2. Second, the financial channels (public investment, private credit, and green foreign direct investment) are incorporated as mediating factors in the relationship between transformation processes and economic growth.
3. Thirdly, the long-term empirical evidence for Vietnam from 1995 to 2023 is provided; additionally, the ARDL model is applied to distinguish between short-run and long-run effects.

AIMS AND OBJECTIVES

Based on the theoretical framework and prior studies, this research aims to assess the impact of digital transformation and green transformation on Vietnam's economic growth and the mediating role of financial channels. The specific objectives are as follows:

- to develop a theoretical framework and an empirical model linking digital transformation, green transformation, and economic growth;
- to analyze the short-run and long-run effects of transformation-related factors on Vietnam's economic growth using the ARDL model; to evaluate the roles of public investment, private credit, and green foreign direct investment (FDI) as financial transmission channels; and to control for the effects of trade openness, the level of societal digitalization, and sustainable development;
- to propose policy implications for promoting sustainable growth based on the harmonization of fiscal, technological, and environmental policies.

METHODS

Research Data

This study uses time series data for Vietnam for the period from 1995 to 2023, compiled from the World Bank (WB), the International Monetary Fund (IMF), the International Energy Agency (IEA), the United Nations Conference on Trade and Development (UNCTAD), the United Nations Development Programme (UNDP), and the General Statistics Office of Vietnam (GSO). The selection of variables is guided by the endogenous growth theory framework and supported by recent empirical

literature on digital transformation, green transformation, and financial development. A detailed description of all variables and their corresponding data sources is provided in Table 1.

Table 1. Description of variables and data sources.

Variable	Variable Description	Unit	Reference Sources	Data Sources
GDP	Economic growth: Logarithm of real GDP (inflation-adjusted)	%	Mankiw, Romer & Weil (1992); Pesaran, Shin & Smith (2001); Le & Hoang, (2021)	WB, GSO
EGDI	Digital transformation: E-Government Development Index	%	Niebel (2018); Katz & Koutroumpis (2013); Su et al. (2013); Nguyen & Bui (2022); Majeed & Ayub (2018).	UNDESA, ITU
GREENI	Green transformation: Renewable energy consumption (% of total final energy consumption)	%	Apergis & Payne (2010); Shahbaz et al. (2017); Rafindadi & Ozturk (2017); Arouri et al. (2014); Radivojević, Rađenović & Dimovski (2024).	WB, IEA
GOVCF	Gross capital formation: % of GDP – proxy for public investment	%	Levine (2005); Égert & Gal (2017); Le & Hoang, (2021).	WB/IMF
PRVT	Domestic credit to private sector (% of GDP)	%	Levine (2005); Beck et al. (2000); Majeed & Ayub (2018); Murshed et al. (2022).	WB/IMF
GFDI	Green foreign direct investment as % of GDP	%	Busu & Trica (2019); Rybárová & Majdúchová (2024); Radivojević et al. (2024).	UNCTAD; OECD
TOPEN	Trade openness: Trade (% of GDP)	%	Rodrik (2006); Azman-Saini et al. (2010); Vu et al. (2023).	WB, GSO
ITUSER	Internet users as % of the population, indicating the level of societal digitalization	%	Su et al. (2013); Alola et al. (2022); Nguyen & Bui (2022).	WB, ITU
SDI	Composite Sustainable Development Index (SDG Index)	%	Sachs et al. (2016, 2021); UNEP (2012); Pham et al. (2022)	UNDP, WB

The stationarity properties of the data are examined using the Augmented Dickey Fuller and Phillips Perron unit root tests. This step ensures that the time series satisfies the necessary conditions for the appropriate application of the ARDL model.

Empirical model

Based on endogenous growth theory (Lucas, 1988; Romer, 1990; Mankiw et al., 1992) and empirical studies by Pesaran, Shin, and Smith (2001) and Le and Hoang (2021), this study uses an ARDL model to analyze the impact of digital transformation and green tranformation on sustainable economic growth in Vietnam over the 1995-2023 period. Based on the theoretical foundations and empirical evidence, the general model is specified as follows:

$GDPt = f (ESDI_t, GREENI_t, GOVCF_t, PRVT_t, GFDI_t, TOPEN_t, ITUSER_t, SDI_t)$.

All variables are expressed in natural logarithms (ln) to mitigate heteroskedasticity and to allow the estimated coefficients to be interpreted as elasticities. The Autoregressive Distributed Lag model is estimated with lag lengths selected according to the Akaike Information Criterion (AIC). The resulting ARDL specification is given as follows:

$$\mathrm{ARDL}(\mathrm{p}, q_1, q_2, \ldots, q_k): \Delta \ln \mathrm{GDP}_\mathrm{t} = \alpha_0 + \sum_{\mathrm{i}=1}^{\mathrm{p}} \emptyset_i \, \Delta \ln \mathrm{GDP}_{\mathrm{t-i}} + \sum_{\mathrm{j}=0}^{q_k} \beta_j \, \Delta X_{t-j} + \lambda_1 \mathrm{lngdp}_{\mathrm{t-1}} + \lambda_2 X_{\mathrm{t-1}} + \varepsilon_\mathrm{t} \,,$$

in which: + X_t is a vector of independent variables (EGDI, GREENI, GOVCF, PRVT, GFDI, TOPEN, ITUSER, SDI); + Δ denotes the first-difference operator; + i,j: are lag indices; + p and qk represent the lag order of the dependent and independent variables; + α_0 is the intercept; + $\emptyset_i$ and β_{kj} are short-run coefficient estimates; + λ_k is the coefficient capturing long-run relationships; + ε_t is a white-noise error term.

This ARDL framework allows for a clear distinction between the short-run and long-run effects of digital transformation, green transformation, and financial and integration-related factors on Vietnam's sustainable economic growth.

Research Methodology

To analyze the relationship between digital transformation, green transformation, and sustainable economic growth in Vietnam over the period 1995–2023, this study adopts the Autoregressive Distributed Lag approach developed by Pesaran, Shin, and Smith (2001). The ARDL framework is particularly suitable in this context for several econometric reasons. First, it accommodates regressors that are integrated of different orders, provided that they are stationary at levels or first differences, that is, I(0) or I(1). Second, the method exhibits desirable small-sample properties, making it appropriate for time series with a limited number of observations. Third, the ARDL specification allows for the simultaneous estimation of

DOI: 10.55643/fcaptp.1.66.2026.4979

short-run dynamics and long-run equilibrium relationships within a unified modeling structure. Accordingly, the empirical analysis follows a systematic procedure consisting of six sequential steps.

1. Data collection, descriptive statistics, and correlation matrix analysis: Data are collected from reliable sources (WB, UNDESA, ITU, UNCTAD, GSO, IMF), and variables are coded according to the research model (please refer to Table 1 for details). Descriptive statistics are conducted to identify the distributional characteristics of each variable, while a correlation matrix is provided to assess preliminary linear relationships among variables.
2. Stationarity testing of time-series data: The time series variables are examined using the Augmented Dickey Fuller (ADF) and Phillips Perron (PP) unit root tests to identify their respective orders of integration. This procedure is conducted to verify that none of the variables is integrated at the second order, I(2), which represents a fundamental prerequisite for the valid application of the ARDL modeling framework.
3. Determination of optimal lag length: The optimal lag structure (p,q) is selected based on the AIC to ensure model adequacy and to avoid residual autocorrelation.
4. Testing for long-run relationships: The presence of cointegration among the variables is first assessed using the ARDL bounds testing approach proposed by Pesaran et al. (2001). When the calculated F statistic is greater than the corresponding upper critical bound, a stable long-run relationship among the variables can be established. To strengthen the robustness of the long-run analysis, the study further applies the Bayer–Hanck (2013) cointegration procedure, which jointly integrates the Engle-Granger, Johansen, Banerjee, and Boswijk tests, thereby providing more reliable inference on long-run relationships.
5. Estimation of the ARDL model: After establishing cointegration, the Autoregressive Distributed Lag (ARDL) model was used to study both the short-term and long-term impacts of digital transformation, green transformation, and financial factors on economic growth. This model incorporates an error correction term (ECT_{t-1}), capturing the rate of adjustment of GDP toward long-term equilibrium after short-term shocks. The empirical framework combines ARDL estimates with the Bayer–Hanck (2013) cointegration method and includes key financial variables such as public investment, private credit, and green foreign direct investment to comprehensively examine the channels through which digitalization and greening shape growth dynamics.
6. Diagnostic and stability tests: The reliability and stability of the estimated model are assessed through a set of standard diagnostic procedures, including the Breusch Godfrey LM test to examine residual autocorrelation, the White test to detect heteroskedasticity, the Jarque Bera test to evaluate the normality of residuals, and the CUSUM and CUSUMSQ tests to verify the stability of model parameters over the sample period.

The model is considered valid only if it satisfies the fundamental econometric assumptions and demonstrates structural stability throughout the entire study period.

RESULTS AND DISCUSSION

Descriptive Statistics and Correlation Matrix of Variables in the Model

Descriptive statistical analysis allows an assessment of variance, standard deviation, and mean values of the variables, thus providing initial insights into the characteristics and potential relationships among economic growth, digital transformation, green transformation, and financial factors in the research model. The dataset consists of 29 observations from 1995 to 2023, as shown in Table 2.

Table 2. Descriptive statistics of variables in the model. *(Source: Authors' calculations from the model, 1995-2023)*

Variable	Mean	Std. dev.	Min	Max
lngdp	12.0121	0.5273	11.1100	12.8450
lnegdi	3.7078	0.4015	2.8651	4.3450
lngreeni	2.9810	0.1827	2.5531	3.3141
lngovcf	3.5086	0.0994	3.3803	3.7531
lnprvt	4.1445	0.6190	2.9169	4.8573
lngfdi	-1.2168	1.3352	-3.0186	1.2362
lntopen	4.8736	0.2196	4.3138	5.2294
lnituser	1.9616	3.3576	-8.9102	4.4326
lnsdi	4.1303	0.2050	3.5222	4.2948

In Table 2, the statistical summary indicates that the variables in the model exhibit different variances; this result reflects uneven development across economic, technological, and financial dimensions. The variable lngdp (economic growth) has a mean value of 12.01 with a relatively low standard deviation value of 0.53; these values suggest that Vietnam's economic growth has maintained a stable long-term trend.

The variables lnegdi (digital transformation) and lnituser (internet user) show relatively high standard deviations, indicating prominent differences in the speed of digitalization over the years, particularly during the early stage of digital transformation (2000–2015). In contrast, lngreeni (green transformation) exhibits a low standard deviation (0.18), which indicates a stable and gradually improving trend in renewable energy application, particularly since 2010, as multiple green growth policies were implemented. Financial variables such as lngovcf, lnprvt, and lngfdi indicate substantial financial expansion, although they remain influenced by global economic cycles.

Overall, the descriptive statistics suggest that Vietnam is simultaneously undergoing the process of digitalization, greening, and financialization of the economy; additionally, the economic growth and digital transformation display stronger volatility compared to the green transformation.

Correlation matrix

The correlation matrix is used to assess linear associations among the variables prior to model estimation. Correlation coefficients range from minus one to one and indicate the direction and strength of pairwise relationships, whether statistically significant or insignificant. This preliminary analysis helps identify notable associations and potential specification concerns. Table 3 presents the correlation matrix of the variables in the model.

Table 3. Correlation matrix of variables in the model. *(Source: compiled from correlation matrix outputs)*

	lngdp	**lnegdi**	**lngreeni**	**lngovcf**	**lnprvt**	**lngfdi**	**lntopen**	**lnituser**	**lnsdi**
lngdp	1.0000								
lnegdi	0.9776 (0.0000)	1.0000							
lngreeni	0.1004 (0.6041)	0.0021 (0.9914)	1.0000						
lngovcf	-0.0532 (0.7841)	0.1046 (0.5891)	-0.6216 (0.0003)	1.0000					
lnprvt	0.9319 (0.0000)	0.9704 (0.0000)	-0.1144 (0.5545)	0.268 (0.1599)	1.0000				
lngfdi	0.5149 (0.0043)	0.5663 (0.0014)	-0.1547 (0.4429)	0.4274 (0.0208)	0.6330 (0.0002)	1.0000			
lntopen	0.8924 (0.0000)	0.9218 (0.0000)	-0.074 (0.7028)	0.2637 (0.1668)	0.9179 (0.0000)	0.5881 (0.0008)	1.0000		
lnituser	0.8274 (0.0000)	0.9035 (0.0000)	-0.2362 (0.2174)	0.3310 (0.0794)	0.9279 (0.0000)	0.5878 (0.0008)	0.881 (0.0000)	1.0000	
lnsdi	0.8121 (0.0000)	0.8834 (0.0000)	-0.1704 (0.3769)	0.2623 (0.1693)	0.9013 (0.0000)	0.5236 (0.0036)	0.8530 (0.0000)	0.9797 (0.0000)	1.0000

In Table 3, the correlation matrix results indicate that the variables exhibit relatively strong linear relationships, particularly among economic growth (lngdp), digital transformation (lnegdi, lnituser), and financial factors (lnprvt, lntopen). Specifically, lngdp shows a strong positive correlation with lnegdi (0.9776), lnprvt (0.9319), and lntopen (0.8924); these results illustrate that the development of digital transformation, private credit, and trade openness has contributed positively to Vietnam's economic growth during the study period.

In contrast, lngreeni (green transformation) exhibits a low and statistically insignificant correlation with lngdp; these results indicate that the greening impact on economic growth remains unclear. This may be attributed to policy lags in renewable energy development and structural industrial transformation. The relationship between lngovcf and lngreeni is negative and statistically significant (-0.6216, $p < 0.01$), implying that when public investment increases, the share of green energy may temporarily decline due to continued concentration of capital in traditional sectors. The high correlation coefficients between lnegdi – lnituser (0.9035) and lnegdi – lnprvt (0.9704) reflect a strong linkage among digital transformation, financial development, and economic growth.

DOI: 10.55643/fcaptp.1.66.2026.4979

Overall, the correlation matrix suggests that severe multicollinearity does not exist; however, the strong relationships among digital transformation and financial variables indicate substantial spillover effects, providing a suitable basis for conducting stationarity tests in the subsequent stage.

Unit Root Tests

This study examines the stationarity properties of the variables by applying the Augmented Dickey-Fuller test and the Phillips-Perron test. The corresponding outcomes of these unit root assessments are summarized and presented in Table 4.

Table 4. Unit root tests. *(Source: Compiled from unit root test results)*

Variable	ADF test		PP test		ADF test		PP test		Conclusion
	t-Statistic	Prob.	t-Statistic	Prob.	t-Statistic	Prob.	t-Statistic	Prob.	
	Level				At first difference				
lngdp	-2.073	0.5611	-2.390	0.3850	-5.021	0.0002	-4.575	0.0011	I(1)
lnegdi	-2.470	0.3432	-2.571	0.2934	-3.995	0.0089	-4.579	0.0011	I(1)
lngreeni	-3.363	0.0566	-2.910	0.1591	-5.212	0.0001	-4.982	0.0002	I(1)
lngovcf	-1.777	0.3920	-1.853	0.6788	-2.696	0.0747	-4.549	0.0013	I(1)
lnprvt	-2.408	0.1394	-1.286	0.8914	-2.604	0.0921	-4.846	0.0004	I(1)
lngfdi	-2.283	0.4434	-3.478	0.0418	-4.709	0.0007	-8.267	0.0000	I(1)
lntopen	-2.206	0.4866	-3.014	0.1283	-3.776	0.0178	-4.868	0.0004	I(1)
lnituser	-15.281	0.0000	-16.126	0.0000	-	-	-	-	I(0)
lnsdi	-11.269	0.0000	-3.749	0.0193	-	-	-	-	I(0)

As reported in Table 4, the unit root test results show that the majority of variables become stationary after first differencing, while lnituser and lnsdi remain stationary in levels. This pattern indicates that the variables included in the empirical model are characterized by a mixed order of integration, encompassing both I(0) and I(1), with no evidence of integration at order two. Accordingly, the application of the Autoregressive Distributed Lag methodology developed by Pesaran et al. (2001) is suitable for estimating both the short-run and long-run relationships among the variables.

Determination of the Optimal Lag Length

To determine the optimal lag length for the model, the study employs the AIC, FPE, HQIC, and SBIC. The results, as shown in Table 5, show that all criteria reach their minimum values at lag length 2.

Table 5. Optimal lag length. *(Source: compiled from optimal lag length results)*

Lag (p)	AIC	FPE	HQIC	SBIC
0	-9.1180	0.0000	-8.9896	-8.6861
1	-21.4084	0.0000	-20.1240	-17.0889
2	-60.9557*	5.9e-37*	-58.5153*	-52.7487*

According to Lütkepohl (2005), this selection ensures a good model fit while mitigating autocorrelation issues. Consequently, an optimal lag length of two is selected for the ARDL model, and this optimal lag length value forms the basis for subsequent long-run relationship testing in the estimation process.

Long-Run Relationship Testing

To examine the existence of long-run cointegration relationships among the variables in the model, the study applies the Bayer–Hanck (2013) cointegration test. This approach has the advantage of jointly combining four conventional cointegration tests, the Engle–Granger (1987), Johansen (1988), Banerjee et al. (1998), and Boswijk (1994), to enhance reliability and reduce bias in cointegration inference.

The results in Table 6 show that while individual tests, such as Engle–Granger and Banerjee, fail to detect cointegration, the Johansen and Boswijk tests reveal a clear long-run relationship among the variables.

Table 6. Bayer–Hanck cointegration test results. *(Source: Model estimation outputs, 2025)*

Test	P-value / Statistic	Interpretation
Engle–Granger	0.8490	No individual cointegration
Johansen	0.0000	Strong cointegration
Banerjee	1.0000	No cointegration
Boswijk	0.0000	Strong cointegration
Bayer–Hanck EG–J	55.589 > 10.637	Cointegration exists
Bayer–Hanck EG–J–Ba–Bo	110.851 > 20.486	Strong cointegration

When combined with the Bayer–Hanck test (EG–J and EG–J–Ba–Bo), the test statistics significantly exceed the 5% critical values and confirm the existence of a strong long-run cointegration relationship among economic growth, digital transformation, green transformation, and financial factors.

Based on these results, the prerequisites for applying the ARDL framework are fully met. Specifically, the variables exhibit mixed orders of integration at I(0) and I(1), with no evidence of integration at order I(2); the optimal lag length is selected as two; and a stable long-run cointegration relationship is confirmed among the variables. Consequently, the study proceeds with the estimation of the ARDL model in the following section to examine both short-run and long-run effects.

Model Estimation

The ARDL estimation results presented in Table 7 clearly illustrate the dynamic relationships between digital transformation (EGDI, Internet users), green transformation (Green Index, SDI), and financial factors (green FDI, public expenditure, private credit, trade openness), and Vietnam's sustainable economic growth over the 1995-2023 period.

Adjustment and Long-Run Equilibrium Effects

The estimated Error Correction Term shows a coefficient of -2.6096 with a p-value of 0.074, indicating statistical significance at the 10 % level. This finding suggests that Vietnam's economic growth adjusts strongly toward its long-run equilibrium after short-run disturbances, with an implied speed of adjustment of approximately 260.96 % per year. Such a rapid convergence toward equilibrium highlights the responsiveness of the Vietnamese economy, reflecting its high degree of openness and its capacity to absorb and adapt to changes in technological conditions and financial policy settings.

Table 7. ARDL estimation results. *(Source: compiled from model estimation results)*

Variables	Coef.	Std.	t-statistic	Prob.	[95% conf. interval]
ADJ					
L1.lngdp	-2.6096	0.3037	-8.59	0.074	[-6.469; 1.250]
Long-run coefficients (LR)					
L1.lnegdi	0.2207	0.0126	17.48	0.036	[0.060; 0.381]
L1.lngreeni	0.0500	0.0078	6.43	0.098	[-0.049; 0.149]
L1.lngovcf	-1.8662	0.0157	-118.80	0.005	[-2.066; -1.668]
L1.Lnprvt	0.6013	0.0075	80.17	0.008	[0.506; 0.697]
L1.lngfdi	-0.0142	0.0009	-16.06	0.040	[-0.025; -0.003]
L1.lntopen	0.6448	0.0111	57.91	0.011	[0.503; 0.786]
L1.lnituser	0.0969	0.0027	36.40	0.017	[0.063; 0.131]
L1.lnsdi	-1.6496	0.0466	-35.37	0.018	[-2.242; -1.057]
Short-run dynamics (SR)					
D1.lnegdi	1.9923	0.2361	8.44	0.075	[-1.008; 4.992]
D1.lngreeni	-0.0827	0.0102	-8.15	0.078	[-0.212; 0.046]
D1.lngovcf	-2.4311	0.2969	-8.19	0.077	[-6.203; 1.341]
D1.Lnprvt	1.0587	0.1459	7.26	0.087	[-0.795; 2.912]
D1.lngfdi	-0.0472	0.0058	-8.09	0.078	[-0.121; 0.027]
D1.lntopen	0.2314	0.0224	10.34	0.061	[-0.053; 0.516]
D1.lnituser	0.3176	0.0390	8.15	0.078	[-0.178; 0.813]
D1.lnsdi	-3.2720	0.4345	-7.53	0.084	[-8.7933; 2.250]
_cons	48.6779	5.7294	8.5	0.075	[-24.121; 121.477]
Obs = 27; R-squared = 0.9981; Adj R-squared = 0.9515; Log likelihood = 164.2044; Root MSE = 0.0029					

DOI: 10.55643/fcaptp.1.66.2026.4979

Long-Run Effects

The long-run ARDL estimation results indicate that digital transformation and green transformation are new growth drivers for Vietnam, although their effectiveness depends strongly on the financial structure.

Digital transformation exerts a positive and significant impact on economic growth. Specifically, a 1% increase in the EGDI and the proportion of Internet users leads to GDP increases of approximately 0.22% and 0.10%, respectively. These findings are consistent with Vu (2013), Bukht and Heeks (2018), and Zhang et al. (2022), who emphasize the role of digitalization in enhancing productivity, fostering innovation, and restructuring the economy toward greater efficiency. At the same time, green transformation also contributes positively to long-run growth, with a coefficient of 0.050, in line with Apergis and Payne (2010) and Shahbaz et al. (2017), who argue that renewable energy and green technologies improve energy efficiency, reduce negative externalities, and enhance productivity.

Financial factors exhibit different effects. Private sector credit (PRVT) has a strong positive impact (0.6013), highlighting the role of financial deepening in supporting technological innovation and green investment, consistent with Levine (2005) and Beck et al. (2012). In contrast, green FDI (GFDI) has a negative effect (-0.0142), suggesting that Vietnam has not yet efficiently absorbed the technologies and ESG standards associated with these capital inflows. This result aligns with UNCTAD's (2023) warning about a "mismatch effect" between green capital flows and absorptive capacity in emerging economies. Notably, public investment (GOVCF) shows a large negative effect (-1.8662), reflecting low capital efficiency and the risk of fragmented investment, consistent with IMF (2023) concerns regarding declining returns and inefficiencies in public investment across ASEAN economies.

Trade openness exerts a strong positive effect (0.6448), confirming the role of economic integration in facilitating technology diffusion, ESG standard transmission, and market expansion. These findings are in line with Dollar and Kraay (2004) and Wacziarg and Welch (2008). Conversely, the Sustainable Development Index (SDI) has a negative impact (−1.6496), reflecting transition costs and resource reallocation during the early stages of achieving the SDGs, consistent with the arguments of Stiglitz et al. (2019) and Sachs et al. (2021).

Short-run dynamics

The short-run estimation results indicate that financial factors play a dominant moderating role in economic growth. Government expenditure exerts a significantly negative effect (-2.4311), reflecting that budget expansion creates inflationary pressure and reduces growth efficiency in the subsequent period. This finding is consistent with the IMF's (2023) warning regarding the low efficiency of public investment in ASEAN economies. In contrast, private sector credit exhibits a strong positive impact (1.0587), confirming its role as a "financial leverage" mechanism that stimulates production, technological innovation, and green investment. This finding is in line with Levine's (2005) argument on the growth-enhancing role of financial development.

Digital transformation generates positive short-run effects: fluctuations in the E-Government Development Index (EGDI) (1.9923) and the Internet user rate (0.3176) suggest that investments in digitalization provide immediate growth momentum through service expansion, digital consumption, and productivity gains. Trade openness also has a positive effect (0.2314), highlighting the role of economic integration in technology diffusion and market expansion.

By contrast, green transformation exerts a mild negative impact (-0.0827), implying that compliance costs with environmental standards and initial investment requirements may dampen growth in the early stages. This result aligns with the argument of initial greening costs proposed by Stiglitz et al. (2019). Green FDI and the sustainable development index also show negative effects (- 0.0472; -3.2720), indicating that technology absorption lags and transition costs weaken short-run growth performance.

Overall, the ARDL model results demonstrate an exceptionally high degree of goodness-of-fit (R^2 = 0.9981; Adjusted R^2 = 0.9515), while the error correction term (ECT) is negative and statistically significant. This confirms the existence of a long-run equilibrium relationship among economic growth, digital transformation, green transformation, financial factors, trade openness, and sustainable development. In the short run, growth is primarily driven by private sector credit, digital transformation, and trade integration, whereas public investment, green FDI, and efforts to achieve the SDGs generate "transition costs" that temporarily reduce growth rates.

In contrast, in the long run, digital transformation, green transformation, private credit, and international integration emerge as key drivers of sustainable growth, although the magnitude of spillover effects depends on capital quality and the economy's technological absorption capacity. The empirical findings suggest that Vietnam is undergoing a structural shift in its growth model from a "capital-labor-intensive" economic model toward one that is "technology-intensive, green-

oriented, and financialized." This transition necessitates financial policy restructuring aimed at improving capital quality, expanding green and digital finance, and reducing transition costs. Overall, digital and green transformations can only deliver sustained positive effects when supported by a strong financial foundation, efficient private investment, and a clear green finance orientation. These insights provide the foundation for the policy implications discussed in the subsequent section.

Diagnostic Tests of Model Assumptions

Within the ARDL framework, verifying the underlying econometric assumptions is essential to ensure the validity and reliability of the estimated results. These assumptions are typically assessed through tests for serial correlation using the Breusch-Godfrey LM procedure, heteroskedasticity based on the White or Breusch Pagan tests, normality of the residuals examined by the Jarque-Bera test, functional form adequacy evaluated via the Ramsey RESET test, and parameter stability analyzed using the CUSUM and CUSUMSQ tests. Failure to satisfy these conditions may result in biased coefficient estimates, thereby weakening the accuracy of empirical inference and subsequent policy implications. Accordingly, this section implements a comprehensive set of diagnostic checks to confirm the robustness and empirical soundness of the ARDL estimation.

Table 8. Results of diagnostic tests for model assumptions. *(Source: compiled from results of diagnostic tests for model assumptions)*

Test	Test criterion	Model result	Conclusion
Serial correlation	Prob > Chi2 > 0.05	0.9380	No serial correlation
Heteroskedasticity	Prob > Chi2 > 0.05	0.4093	No heteroskedasticity
Normality of residuals	Prob > Chi2 > 0.05	0.1976	Residuals are normally distributed
Functional form	Prob > F > 5%	0.1651	Correct functional form; no omitted key variables

The CUSUM test results indicate no evidence of structural change in the model. This is reflected by the test statistic remaining below the critical bounds and the CUSUM plot lying entirely within the 95% confidence interval. These findings confirm that the regression model remains stable throughout the study period from 1995 to 2023.

Table 9. Model stability test results. *(Source: compiled from model stability test outputs)*

Test	Test statistic	Critical value			Conclusion
		1%	5%	10%	
CUSUM	0.3189	1.1430	0.9479	0.8499	Stable model (No structural change)

In Tables 8 and 9, and Figure 1, after conducting the post-estimation diagnostic tests for the ARDL model, the results indicate that all diagnostic criteria are satisfied, with no evidence of structural breaks and with parameters remaining stable over time.

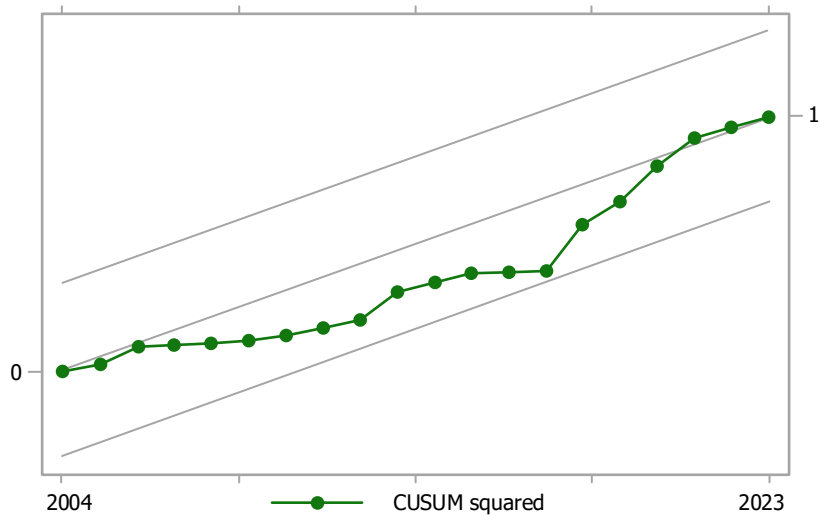

Figure 1. CUSUM Squared. *(Source: compiled from model outputs, 2025)*

DOI: 10.55643/fcaptp.1.66.2026.4979

CONCLUSIONS

This study examines the impacts of digital transformation, green transformation, and financial factors on sustainable economic growth in Vietnam over the period 1995–2023 using the ARDL approach. The empirical results confirm the existence of a stable long-run cointegrating relationship among the variables, indicating that both digital and green transformation processes play a significant role in fostering economic growth. In the long term, digital transformation, measured by the E-Government Development Index and internet usage rate, has a positive and statistically significant impact on GDP growth, highlighting the importance of digital infrastructure, information technology development, and digital skills in enhancing productivity and economic efficiency. Green transformation also contributes positively to economic growth; however, the Sustainable Development Index suggests the presence of short-term adjustment costs, reflecting transitional frictions during the initial phases of the greening process. Financial factors, including public investment, private sector credit, and green foreign direct investment, emerge as critical transmission channels through which digitalization and greening translate into growth outcomes, underscoring the increasing role of financialization in supporting structural transformation. Moreover, trade openness reinforces these effects by facilitating technology spillovers and accelerating the diffusion of international environmental, social, and governance standards. Overall, the findings provide robust empirical support for targeted financial policies aimed at reallocating financial resources toward digital and green investments, thereby aligning Vietnam's financial system with its long-term sustainable economic growth objectives.

Based on the empirical findings, three key groups of policy implications are proposed:

- First, a sufficient financing mechanism for digital transformation is necessary. It is necessary to expand financial channels that support digitalization in both enterprises and the public sector through increased investment in digital technologies, innovation funds, and preferential credit for SMEs undertaking digital transformation. The government should improve mechanisms for mobilizing private capital and public–private partnerships (PPPs) in digital infrastructure, while encouraging financial institutions to develop digital financial products, fintech solutions, and digital payment services in order to reduce transaction costs and improve access to finance.
- Second, green finance for sustainable economic growth should be developed and expanded. The results indicate that green transformation only promotes growth when financial resources are allocated efficiently. Accordingly, Vietnam needs to develop green financial markets through green bonds, green credit, carbon funds, and green banking to reduce the cost of capital for renewable energy projects, cleaner production, and circular economy models. Green tax mechanisms, ESG-based incentives, and carbon pricing schemes should be implemented promptly to support firms in transitioning toward low-emission business models.
- Third, international integration and ESG standards need to be implemented. Trade openness and green FDI should be leveraged as key channels for the diffusion of digital and green technologies, particularly through trade agreements such as the EVFTA, CPTPP, and RCEP. The government should impose ESG requirements on green FDI inflows and establish green financial criteria for foreign investors, ensuring that capital inflows contribute to green transformation, digitalization, and productivity enhancement in Vietnam.

Overall, the government should adopt an integrated approach to effectively coordinate digital transformation, green transformation, and sustainable economic growth objectives. Policy design must ensure coherence in financial resources, human capital, and institutional frameworks in order to avoid policy conflicts and enhance implementation effectiveness. The integration of these two transformation processes will form the foundation for a sustainable, inclusive, and adaptive growth model amid the development of the digital economy, economic greening, and climate change adaptation. This is also a key factor enabling Vietnam to achieve rapid and sustainable growth, fulfill its net-zero commitment by 2050, and enhance its competitive position in the global digital and green economy.

Limitations and Directions for Future Research

This study employs single-country time-series data, which limits its ability to fully capture regional and global comparative dynamics. Therefore, future research may extend in the following directions:

1. Conduct comparative analyses using panel models (Panel-ARDL or CS-ARDL) for ASEAN countries or other emerging economies.
2. Examine the mediating role of digital finance and green finance in the transmission mechanisms affecting economic growth.
3. Apply nonlinear models (NARDL, QARDL) to assess asymmetric effects of digital and green investments.

4. Evaluate the impacts of major shocks (financial crises, COVID-19, geopolitical tensions) on the long-term trajectories of digital and green transformation.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

FUNDING

This research is partly funded by University of Finance – Marketing.

CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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ВПЛИВ ЦИФРОВОЇ ТА ЗЕЛЕНОЇ ТРАНСФОРМАЦІЇ НА СТАЛИЙ ЕКОНОМІЧНИЙ РОЗВИТОК: ЕМПІРИЧНІ ДАНІ З В'ЄТНАМУ

Подвійний перехід до цифровізації та зеленого розвитку став стратегічним пріоритетом для економік, що розвиваються, які прагнуть сталого зростання. Однак емпіричні докази щодо одночасних механізмів фінансової передачі цих двох трансформацій залишаються обмеженими. У цьому дослідженні розглянуті короткострокові й довгострокові наслідки впливу цифрової трансформації та зеленої трансформації на сталий економічний розвиток В'єтнаму протягом 1995–2023 років з особливим акцентом на фінансові чинники, що підтримують порядок денний подвійного переходу. Використовуючи щорічні макрофінансові часові ряди та модель авторегресивного розподіленого відставання (ARDL), доповнену тестом коінтеграції Байєра–Ганка, аналіз інтегрує ключові показники цифровізації (EGDI та використання інтернету), зеленої трансформації (частка відновлюваної енергетики та індекс ЦСР), а також фінансові змінні, включаючи державні інвестиції, внутрішнє кредитування приватного сектора та зелені прямі іноземні інвестиції, з відкритістю торгівлі, що захоплює глобальну інтеграцію. Результати підтверджують існування стабільних довгострокових відносин співпраці, а це свідчить про те, що цифровізація та зелена трансформація мають позитивний і статистично значущий вплив на сталий економічний розвиток. Фінансові чинники відіграють роль каталізатора: кредитування приватного сектора в середньому становило понад 90% ВВП з 2015 року й досягло 128,68% 2023 року, сприяючи поширенню цифрових технологій і підтримці проєктів відновлюваної енергетики; водночас державні інвестиції (приблизно 7% ВВП) прискорюють модернізацію зеленої та цифрової інфраструктури. Натомість припливи зелених ПІІ залишаються помірними, що підкреслює невикористаний потенціал капіталу, орієнтованого на ESG. Результати підкреслюють необхідність узгоджених фінансових і фіскальних рамок для розширення зелених фінансових інструментів, підвищення ефективності зелених і цифрових державних інвестицій, залучення якісних зелених ПІІ та узгодження фінансових ринків із цілями сталого розвитку. Це дослідження надає нові фінансові емпіричні дані для В'єтнаму та інсайти, релевантні для інших економік, що розвиваються, які прагнуть фінансово орієнтованої цифрової та зеленої трансформації для сталого розвитку.

Ключові слова: цифрова трансформація, зелена трансформація, сталий економічний розвиток, зелені фінанси, державні інвестиції, національний кредит, зелені ПІІ, модель ARDL, В'єтнам

JEL Класифікація: C32, O33, Q01, Q56

DOI: 10.55643/fcaptp.1.66.2026.4979