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DIGITAL TRANSFORMATION AND SUSTAINABLE DEVELOPMENT IN SOUTHEAST ASIAN COUNTRIES: THE MODERATING ROLE OF GOVERNMENT EFFECTIVENESS

Bui The Sang*, Tran Phuoc

Ho Chi Minh City University of Industry and Trade

*Email: *6023250004@huit.edu.vn*

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ABSTRACT

This study examines the impact of digital transformation on the environmental dimension of sustainable development in six Southeast Asian countries over the period 2002–2022. Environmental sustainability is proxied by consumption-based CO_2 emissions per capita, with government effectiveness examined as a moderating factor. Using panel data, the study applies the Method of Moments Quantile Regression (MMQR) to capture heterogeneous effects across emission levels, while bootstrap quantile regression (BSQ) is employed as a robustness check. The results show that digital transformation significantly reduces emissions across all quantiles, with stronger mitigation effects observed at higher emission levels, indicating greater environmental benefits in carbon-intensive economies. However, government effectiveness weakens this emission-reducing effect. This implies that the environmental impact of digital transformation depends on institutional quality and highlights the need to align digital strategies with environmental governance to achieve sustainable emission reductions.

Keywords: Digital transformation, government effectiveness, MMQR, sustainable development.

1. INTRODUCTION

Climate change poses a serious threat to sustainable global development. Carbon dioxide (CO_2) emissions are a primary driver of the greenhouse effect and long-term global warming. Despite increasing international mitigation efforts, global carbon intensity remains high. According to Our World in Data [1], global CO_2 emissions per capita remain around 4.9 tonnes per person per year. This reflects the continued reliance of economic activities on carbon-intensive energy sources. As a result, concerns about environmental degradation and sustainable development are increasing, particularly in rapidly growing regions.

Southeast Asian countries have experienced rapid economic growth, industrial expansion, and deeper trade integration. These developments have led to a notable increase in carbon emissions over recent decades. As these economies become more integrated into global value chains, emissions are generated not only domestically but also through international trade and final consumption. This makes environmental challenges more complex and difficult to manage.

In this context, digital transformation has emerged as a potential pathway to decouple economic growth from carbon emissions. Digital technologies, including big data analytics, artificial intelligence, and the Internet of Things, can improve energy efficiency and optimize production and consumption processes. They also support the diffusion of cleaner technologies. However, the environmental effects of digital transformation remain ambiguous.

Efficiency gains may reduce emissions, but increased energy demand and production scale may offset these benefits.

Although the literature on digital transformation and environmental sustainability is expanding, empirical evidence remains inconclusive, especially for emerging economies. Cross-country panel studies suggest that digital transformation can reduce carbon emissions through efficiency improvements and technological upgrading [2-3]. However, other studies highlight rebound effects caused by rising electricity consumption and economic expansion. These effects may lead to heterogeneous outcomes across countries [4]. In addition, most existing studies focus on production-based emissions and overlook emissions embodied in trade and consumption. Given the region's strong global integration, consumption-based CO_2 emissions per capita provide a more comprehensive measure of environmental pressure.

Institutional quality, particularly government effectiveness, may further influence the environmental outcomes of digital transformation. Government effectiveness reflects the ability of public institutions to design and implement policies that guide technological change toward sustainability. Strong governance may enhance environmental benefits. However, it may also weaken them if policy priorities emphasize economic expansion over environmental goals.

Against this backdrop, this study examines the impact of digital transformation on consumption-based CO_2 emissions per capita in six Southeast Asian countries – Vietnam, Thailand, Indonesia, Singapore, Malaysia, and Cambodia – over the period 2002–2022. These countries were selected based on the availability and consistency of annual data for all study variables, while the remaining countries in the region were excluded because of substantial missing or discontinuous observations. It also investigates the moderating role of government effectiveness. By integrating digital transformation, institutional quality, and consumption-based emissions into a unified framework, this study provides new evidence on the environmental consequences of digital transformation. It also offers policy-relevant insights for promoting sustainable development in emerging economies.

2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Theoretical background

Digital transformation is commonly viewed as a continuous and multidimensional process in which digital technologies act as key enablers of fundamental changes in how organizations and economies operate and create value [5-6]. Prior studies emphasize that digital transformation goes beyond mere technology adoption and involves innovation in business models, organizational restructuring, and strategic adjustment to enhance efficiency and competitiveness [7-9]. In terms of measurement, digital transformation is inherently multidimensional, encompassing technological infrastructure, digital skills, innovation capacity, and the integration of digital technologies into economic activities [10]. Due to data limitations in cross-country panel settings, the literature often relies on proxy variables to capture specific dimensions of digital transformation.

In this study, digital transformation is proxied by the share of information and communication technology (ICT) goods exports in total goods exports. This measure reflects the development of the digital technology sector and the degree of an economy's participation in global digital value chains. It is particularly relevant for Southeast Asian economies, where digital transformation is closely linked to export-oriented industrialization, trade integration, and technology diffusion through international markets.

Although ICT exports do not fully capture all dimensions of digital transformation, they provide a consistent and comparable indicator of the technological and production-side aspects of digitalization across countries and over time. This proxy has been widely used in prior empirical studies examining the relationship between ICT and environmental or economic outcomes [3,4,11]. Therefore, it is considered appropriate for the empirical framework of this study, while acknowledging that future research may benefit from incorporating more comprehensive composite digitalization indices. Moreover, the focus on ICT exports aligns with the study's emphasis on globalization and consumption-based emissions, as digital trade plays a key role in shaping cross-border production and carbon flows.

Sustainable development is commonly defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs [12]. Classical studies emphasize that sustainability requires maintaining economic welfare while preserving natural capital and ecosystem capacity [13], as well as balancing the three pillars of economic growth, social progress, and environmental protection [14]. At the policy level, the United Nations operationalized this concept through the 17 Sustainable Development Goals (SDGs), highlighting the comprehensive and action-oriented nature of sustainable development at the global scale [15]. In empirical research, sustainable development is often proxied by environmental indicators such as CO_2 emissions, ecological footprint, or air quality measures, which capture environmental pressure and resource-use efficiency [16, 17].

In this study, sustainable development is measured using consumption-based CO_2 emissions per capita, which better reflects a country's carbon footprint under globalization by incorporating emissions embodied in international trade [18, 19]. The choice of consumption-based CO_2 emissions per capita is particularly relevant in the context of digital transformation and globalization. Unlike production-based measures, consumption-based emissions account for carbon embodied in international trade, thereby capturing the full environmental footprint of domestic consumption. This distinction is critical in Southeast Asian economies, where digital transformation is closely associated with trade integration, global value chain participation, and cross-border digital activities. As digital technologies facilitate production fragmentation, e-commerce, and international outsourcing, emissions may be shifted across borders rather than reduced globally. Therefore, using consumption-based CO_2 emissions provides a more comprehensive and theoretically consistent measure for assessing the environmental impact of digital transformation. This approach also helps avoid underestimating environmental pressures in countries that increasingly rely on imported carbon-intensive goods while expanding digitally driven economic activities.

Government effectiveness is defined as the capacity of the state to design and implement public policies, deliver high-quality public services, and use public resources efficiently to promote economic growth and social welfare [20, 21]. This concept encompasses not only the quality of the public administration but also the independence of the public sector from political pressures and the effectiveness of policy formulation and implementation [22, 23]. In empirical research, government effectiveness is commonly regarded as a key institutional factor that plays a moderating role by amplifying the positive impacts of development drivers such as digital transformation and green finance on sustainable development [24, 25]. In this study, government effectiveness is measured using the Government Effectiveness indicator from the Worldwide Governance Indicators (WGI), which captures perceptions of public service quality and policy implementation capacity and is standardized on a scale ranging from -2.5 to +2.5.

Drawing on the diffusion of innovation theory [26], digital transformation proxied by ICT reflects the extent to which digital technologies are adopted across economic agents. As ICT diffuses, firms and public institutions can enhance operational efficiency, optimize resource allocation, and improve energy management, thereby contributing to lower per capita CO_2 emissions. However, the environmental impact of digital transformation is not automatic and is highly contingent upon the institutional context. From an institutional theory perspective [27], government effectiveness shapes both the implementation process and the strategic orientation of digital technologies. In growth-oriented institutional environments, particularly in developing and emerging economies, effective governments may prioritize the use of ICT to expand productive capacity and stimulate economic activity rather than to pursue environmental objectives.

Specifically, government effectiveness moderates the impact of digital transformation on environmental outcomes through several channels. In contexts with high government effectiveness, digital transformation is more likely to be accompanied by stringent environmental regulations, efficient policy implementation, and better allocation of digital resources toward energy efficiency and green innovation. This enhances the potential of digital technologies to reduce CO_2 emissions.

In contrast, in countries with low government effectiveness, weak regulatory enforcement and policy inefficiencies may lead digital transformation to primarily support economic expansion and energy-intensive activities, thereby increasing CO_2 emissions.

Therefore, government effectiveness conditions the direction and magnitude of the relationship between digital transformation and environmental outcomes, acting as a key moderating factor.

2.2. Literature review

While the theoretical framework highlights the mechanisms linking digital transformation and environmental outcomes, empirical evidence remains mixed across different contexts. Therefore, the following section reviews the existing literature to clarify these relationships.

A growing body of empirical literature highlights the pivotal role of digital transformation in shaping environmental outcomes across countries and firm-level contexts. Early cross-country evidence suggests that ICT can mitigate carbon emissions by moderating the adverse environmental effects of globalization and economic integration, particularly in developing regions [3]. Complementary qualitative and case-based studies further emphasize that digital transformation can support early warning systems, improve energy infrastructure efficiency, enhance resource management, and facilitate participatory climate adaptation, thereby strengthening climate resilience and sustainable urban development when appropriately designed and implemented [28]. At the macro level, panel and time-series analyses indicate that ICT diffusion contributes to long-run reductions in CO_2 emissions, especially in low- and middle-income economies, although its environmental benefits tend to weaken as income levels rise and production scales expand [4, 29].

Recent firm-level evidence consistently shows that digital transformation significantly reduces carbon emission intensity by improving technological innovation, energy efficiency, internal control, and environmental information disclosure [30, 31]. These effects are often stronger in institutional environments characterized by robust intellectual property protection and advanced capital intensity. Beyond digitalization alone, technological progress and green technologies have been identified as key channels through which digital transformation enhances environmental performance [32, 33]. Moreover, emerging studies highlight the complementary roles of fintech, financial inclusion, and green finance in amplifying the emission-reducing effects of digital transformation, while underscoring the importance of government effectiveness and institutional quality in shaping these outcomes [34, 35]. Evidence from the European Union and emerging economies further confirms that digitalization positively contributes to sustainable development outcomes, including reductions in carbon emissions and progress toward the Sustainable Development Goals, although urbanization and resource-intensive growth patterns may offset part of these gains [36].

Overall, the literature suggests that digital transformation generally supports environmental sustainability through efficiency gains and technological upgrading; however, its effectiveness is highly context-dependent and critically conditioned by income levels, institutional frameworks, energy structures, and the alignment of digital transformation with green governance.

From a theoretical perspective, this relationship can be grounded in Rogers' Diffusion of Innovation theory [26], which explains how new technologies are gradually adopted and disseminated across economic agents over time. The theory suggests that the adoption of digital technologies depends on their perceived advantages, compatibility, and ease of use, which in turn determines the speed and extent of ICT diffusion. As digital technologies spread, they enable firms and institutions to improve operational efficiency, optimize resource allocation, and enhance energy management, thereby contributing to environmental improvements such as reduced CO_2 emissions. Importantly, the theory also implies that the outcomes of digital transformation are not uniform but evolve with the depth of adoption and are shaped by institutional conditions, which is consistent with the heterogeneous empirical findings discussed above.

3. METHODOLOGY

3.1. Econometric model, Variable Description and Data

3.1.1. Econometric model and Hypotheses

To analyze and quantify the impact of digital transformation on sustainable development, as well as to examine the moderating role of government effectiveness, this study incorporates moderating and control variables such as government effectiveness, economic growth, and trade openness. Following the previous studies, the models are given as:

$$CBE_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 GE_{it} + \beta_3 GDP_{it} + \beta_4 OPE_{it} + \varepsilon_{it} \quad (1)$$

$$CBE_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 GE_{it} + \beta_3 (GE_{it} x ICT_{it}) + \beta_4 GDP_{it} + \beta_5 OPE_{it} + \varepsilon_{it} \quad (2)$$

Model (1) is specified to examine the direct effect of digital transformation on consumption-based CO_2 emissions per capita.

Model (2) is specified to test the moderating role of government effectiveness in the relationship between digital transformation and environmental outcomes. The interaction term GExICT allows for an assessment of whether government effectiveness amplifies or attenuates the impact of digital transformation on consumption-based CO_2 emissions per capita.

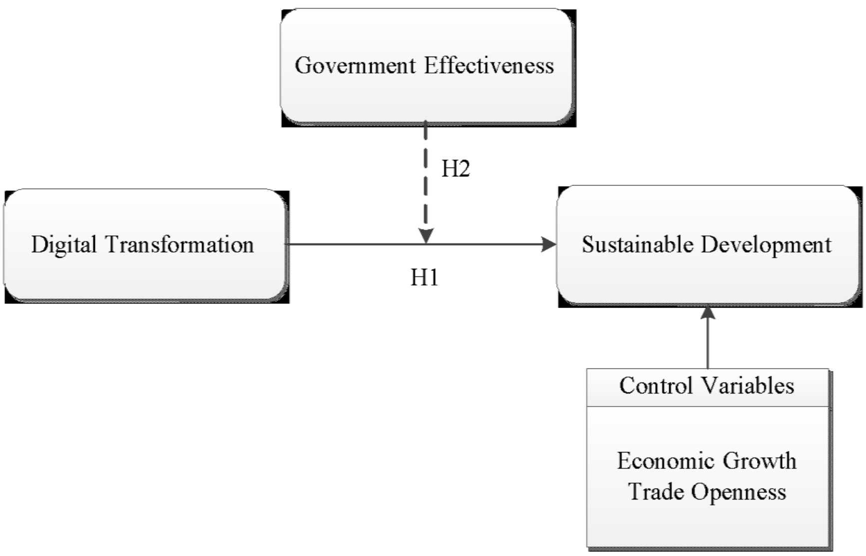

Figure 1. Econometric model (*Source: Authors' construction*)

Building on the theoretical arguments and empirical evidence discussed above, the research hypotheses are developed as follows. First, prior studies suggest that digital transformation can reduce CO_2 emissions by improving energy efficiency, optimizing production processes, and facilitating technological upgrading [2-4,11]. Therefore, digital transformation is expected to contribute positively to sustainable development by reducing consumption-based CO_2 emissions per capita. Second, institutional theory indicates that government effectiveness shapes how digital technologies are implemented and whether they are directed toward environmental or growth-oriented objectives [24,25,27]. Accordingly, government effectiveness is expected to moderate the relationship between digital transformation and sustainable development.

Based on this reasoning, the following hypotheses are proposed:

H1: Digital transformation (ICT) reduces consumption-based CO_2 emissions per capita.

H2: Government effectiveness (GE) moderates the relationship between digital transformation (ICT) and consumption-based CO_2 emissions per capita.

3.1.2. Variable Description and Data

This study employs panel data comprising six cross-sectional units (N = 6), 21 annual observations for each country (T = 21), and a total of 126 country-year observations, collected from multiple reliable international databases to test the proposed research hypotheses. The dependent variable is consumption-based CO_2 emissions per capita (CBE), measured in $MtCO_2$ per capita and obtained from the Global Carbon Atlas database. The main independent variable is digital transformation (ICT), proxied by the share of information and communication technology goods exports in total merchandise exports, and sourced from the World Development Indicators (World Bank). In addition, several control variables are incorporated to ensure the robustness of the empirical model. These include economic growth (GDP), measured as the natural logarithm of GDP per capita; trade openness (OPE), measured as the ratio of total exports and imports to GDP; and government effectiveness (GE), which captures institutional quality and ranges from -2.5 to +2.5. All control variables are obtained from the World Bank database. Overall, the dataset provides a comprehensive analytical framework for examining the effects of digital transformation and macroeconomic factors on sustainable development outcomes in Southeast Asia during the 2002-2022 period.

3.1.3. Expected Effects of Explanatory Variables

Based on theoretical considerations and prior empirical evidence, the expected effects of the explanatory variables on consumption-based CO_2 emissions per capita are summarized in Table 1.

Table 1. Expected effects of explanatory variables

Variable	Expected sign	Supporting studies
ICT	-	[2]; [3]; [4]; [11]
GDP	+	[37]; [38]; [39]; [40]
OPE	+	[41]; [42]; [43]
GE	+	[44]; [45]; [46]

Note: "-" indicates an emission-reducing effect, while "+" indicates an emission-increasing effect.

3.2. Methods of analysis

The MMQR proposed by Machado & Silva [47] is employed to capture heterogeneous effects across the conditional distribution of the dependent variable. Compared with conventional mean-based estimators, MMQR allows for the estimation of both location and scale effects and is robust to heteroskedasticity, non-normality, and outliers. In addition, it accommodates panel data with fixed effects, thereby controlling unobserved heterogeneity. However, MMQR requires a sufficiently large sample size for reliable estimation and involves more complex interpretation than standard regression models. The method is particularly appropriate when relationships vary across quantiles and assume correctly specified models with no severe multicollinearity. These conditions are satisfied in the present study.

First, descriptive statistics are conducted to provide a preliminary overview of the dataset. The Jarque-Bera (JB) test is then employed to examine the normality of the data [48]. Next, slope homogeneity is tested using the procedure proposed by Pesaran & Yamagata [49] to assess whether the regression coefficients are identical across cross-sectional units. Cross-sectional dependence among the panel units is examined using the test developed by Pesaran [50]. Subsequently, the Im-Pesaran-Shin (IPS) panel unit root test [51] is employed to examine the stationarity properties of the variables. The presence of long-run relationships among the variables is investigated using the panel cointegration tests developed by Pedroni [52] and Kao [53].

Thereafter, the MMQR is employed on a balanced panel dataset to provide a robust framework for examining the effects of the explanatory variables across different quantiles of the dependent variable. Finally, BSQ regression is applied as a robustness check to complement the MMQR estimates. The BSQ regression approach relies on resampling techniques to obtain more accurate estimates of the empirical sampling distribution of the model parameters.

4. RESULTS AND DISCUSSION

4.1. Results and discussion

Table 2. Descriptive Statistics

	CBE	ICT	GE	GDP	OPE
Mean	7.782	18.478	0.388	8.422	160.437
Std. Dev.	11.004	14.815	0.989	1.343	99.569
Min	0.612	0.05	-1.002	5.858	32.972
Max	44.900	51.4	2.470	11.411	437.326
p1	0.622	0.05	-1.001	5.958	37.421
p99	38.807	50.74	2.408	11.290	425.363
Skew.	1.843	0.297	0.697	0.437	1.278
Kurt.	4.932	1.843	2.430	2.633	3.753
J-B	90.91	8.879	11.91	4.722	37.27
J-B p-value	0.000	0.012	0.003	0.094	0.000

Table 2 presents the descriptive statistics of the key variables, including consumption-based CO_2 emissions per capita (CBE), information and communication technology (ICT), economic growth (GDP), trade openness (OPE), and government effectiveness (GE). ICT and OPE show relatively high mean values, whereas GE records a lower average level, reflecting cross-country institutional differences. CBE exhibits substantial variation, as indicated by its large standard deviation. The wide range between minimum and maximum values confirms considerable heterogeneity across countries. Skewness and kurtosis statistics suggest non-normal distributions, which is supported by the Jarque-Bera test results, rejecting normality for most variables (p-value < 0.1). These features justify the use of advanced panel econometric techniques in subsequent analyses.

Table 3. Slope Heterogeneity Test

		Test	Stat	p-value
Model 1	CBE ICT GE GDP OPE	Delta Adjusted Delta	1.703* 2.015**	0.089 0.044
Model 2	CBE ICT GE GExICT GDP OPE	Delta Adjusted Delta	0.900 1.102	0.368 0.271

*Asterisks ** and * show significance levels at 5% and 10%.*

Table 3 presents the results of the slope heterogeneity tests for the Southeast Asian sample. The findings indicate statistically significant slope heterogeneity in Model 1 (p-value < 0.1 and p-value < 0.05), implying that the impacts of ICT, government effectiveness, economic growth, and trade openness on consumption-based CO_2 emissions vary across countries. In contrast, the slope heterogeneity tests for Model 2, which includes the interaction term between government effectiveness and ICT (GExICT), fail to reject the null hypothesis of slope homogeneity. Overall, these results support the use of econometric approaches that account for cross-country heterogeneity in subsequent estimations.

Table 4. Cross-sectional dependency analysis

Variables	Pesaran's CD Stat	p-value	abs(corr)
CBE	12.09	0.000	0.681
ICT	0.77	0.439	0.587
GE	3.05	0.002	0.368
GDP	17.31	0.000	0.975
OPE	4.59	0.000	0.490

Table 4 presents the results of Pesaran's [50] cross-sectional dependence (CD) test, revealing significant cross-sectional dependence for most variables, as the null hypothesis of cross-sectional independence is rejected for CBE, GE, GDP, and OPE (p-values < 0.05), while ICT does not exhibit significant dependence. These findings suggest that the sample countries are subject to common shocks and spillover effects, thereby requiring econometric techniques that account for cross-sectional dependence; accordingly, we employ the IPS panel unit root test [51] to examine the stationarity properties of the variables.

Table 5. Unit Root Analysis

	At Level	At I (1)
Variables	T-bar Stat	t-bar Stat
CBE	-3.4319***	
ICT	-1.7494	-4.5070***
GE	-1.0373	-5.4697***
GDP	-0.9015	-3.7506***
OPE	-1.3788	-4.7331***

*Asterisks *** show significance levels at 1%.*

Table 5 presents the panel unit root test results, showing that CBE is stationary at level, while ICT, GE, GDP, and OPE become stationary after first differencing, indicating integration of order one, I(1). These findings suggest a mixed order of integration among the variables. Accordingly, panel cointegration techniques are appropriate for the subsequent analysis.

Table 6. Cointegration Analysis

Pedroni cointegration test [52]	Model 1		Model 2	
	Stat	p-value	Stat	p-value
Modified Phillips-Perron t	0.2101	0.4168	1.5358	0.0623
Phillips-Perron t	-3.2908	0.0005	-2.6882	0.0036
Augmented Dickey-Fuller t	-2.8302	0.0023	-0.9647	0.1673
Kao cointegration test [53]				
	Stat	p-value	Stat	p-value
Modified Dickey-Fuller t	-7.1624	0.0000	-5.1358	0.0000
Dickey-Fuller t	-5.2376	0.0000	-4.8035	0.0000
Augmented Dickey-Fuller t	-5.4417	0.0000	-5.2054	0.0000
Unadjusted modified Dickey-Fuller t	-7.5246	0.0000	-7.9959	0.0000
Unadjusted Dickey-Fuller t	-5.2904	0.0000	-5.4557	0.0000

Table 6 reports the results of the panel cointegration tests based on the methodologies of Pedroni [52] and Kao [53] for the estimated models. The results provide strong evidence of cointegration among the variables in all models, as most test statistics are statistically significant at conventional levels. These findings indicate the existence of a long-run equilibrium relationship among the variables, suggesting that they move together over time despite potential short-run fluctuations. However, cointegration tests do not capture potential heterogeneity across the distribution of the dependent variable. Therefore, the MMQR approach is employed as a complementary method to examine distributional effects beyond the average relationship.

Table 7. MMQR Model-1

Variables	Location	Scale	Q25	Q50	Q75	Q90
ICT	-0.202*** (0.036)	-0.038 (0.026)	-0.170*** (0.029)	-0.198*** (0.034)	-0.229*** (0.049)	-0.259*** (0.073)
GE	2.851*** (1.112)	0.702 (0.801)	2.254** (0.884)	2.764*** (1.054)	3.337** (1.511)	3.885** (2.125)
GDP	2.994*** (0.655)	-0.172 (0.472)	3.140*** (0.518)	3.015*** (0.621)	2.875*** (0.893)	2.741** (1.218)
OPE	0.064** (0.006)	0.010** (0.004)	0.055*** (0.005)	0.063*** (0.006)	0.071*** (0.008)	0.080*** (0.014)
Constant	-25.108*** (5.405)	2.333 (3.893)	-27.094*** (4.277)	-25.396*** (5.129)	-23.492*** (7.374)	-21.669** (10.099)

*Note: Q25, Q50, Q75, and Q90 represent the 25th, 50th, 75th, and 90th conditional quantiles. The parentheses "()" show the standard errors. Asterisks *** and ** show significance levels at 1% and 5%.*

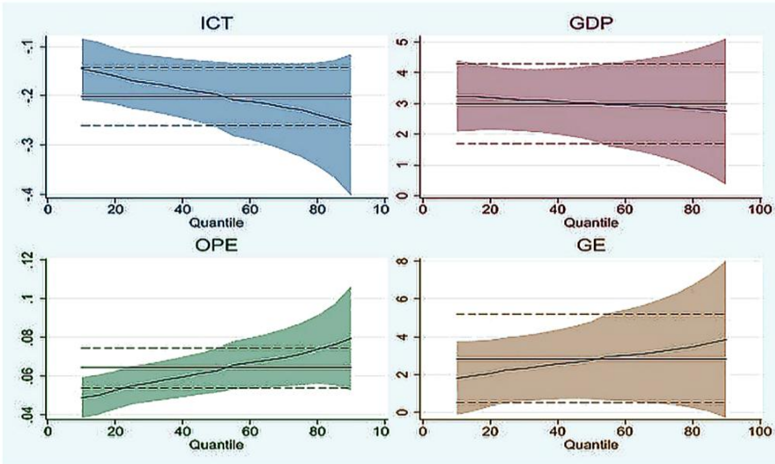

Figure 2. MMQR Model-1 (*Source: Authors' estimations using Stata*)

Based on the MMQR estimates reported in Table 7 and illustrated in Figure 2, ICT exerts a negative and highly significant effect (1% level) on consumption-based CO_2 emissions per capita across all quantiles. Specifically, the estimated coefficients are -0.170 at Q25, -0.198 at Q50, -0.229 at Q75, and -0.259 at Q90, all statistically significant at the 1% level, indicating that the emission-reducing impact of digital transformation becomes stronger as countries move toward higher emission levels. This quantile-dependent pattern supports Hypothesis H1 and is consistent with prior empirical evidence [2-4,11]. In contrast, government effectiveness (GE) shows a positive and statistically significant association with emissions across the conditional distribution, suggesting that governance improvements may coincide with higher emissions in more carbon-intensive economies [44-46]. Regarding the control variables, economic growth (GDP) and trade openness (OPE) both exhibit positive and statistically significant effects at the 1% level, implying that expanding production, consumption, and trade-related activities increases energy demand and transportation intensity, thereby contributing to higher carbon emissions.

Table 8. MMQR Model-2

Variables	Location	Scale	Q25	Q50	Q75	Q90
ICT	-0.185*** (0.036)	0.001 (0.025)	-0.185*** (0.031)	-0.185*** (0.036)	-0.184*** (0.046)	-0.183*** (0.068)
GE	2.824*** (0.984)	0.449 (0.683)	2.392*** (0.848)	2.820*** (0.980)	3.106** (1.262)	3.569** (1.872)
GExICT	0.109*** (0.042)	0.029 (0.029)	0.081** (0.036)	0.108*** (0.042)	0.127** (0.053)	0.157** (0.081)
GDP	3.263*** (0.600)	-0.212 (0.417)	3.466*** (0.517)	3.264*** (0.598)	3.129*** (0.771)	2.911*** (1.135)
OPE	0.054*** (0.006)	0.007* (0.004)	0.047*** (0.005)	0.054*** (0.006)	0.059*** (0.008)	0.066*** (0.013)
Constant	-27.222*** (4.974)	2.042 (3.456)	-29.186*** (4.285)	-27.239*** (4.963)	-25.940*** (6.395)	-23.832** (9.406)

*Note: Q25, Q50, Q75, and Q90 represent the 25th, 50th, 75th, and 90th conditional quantiles. The parentheses "()" show the standard errors. Asterisks *** and ** show significance levels at 1% and 5%.*

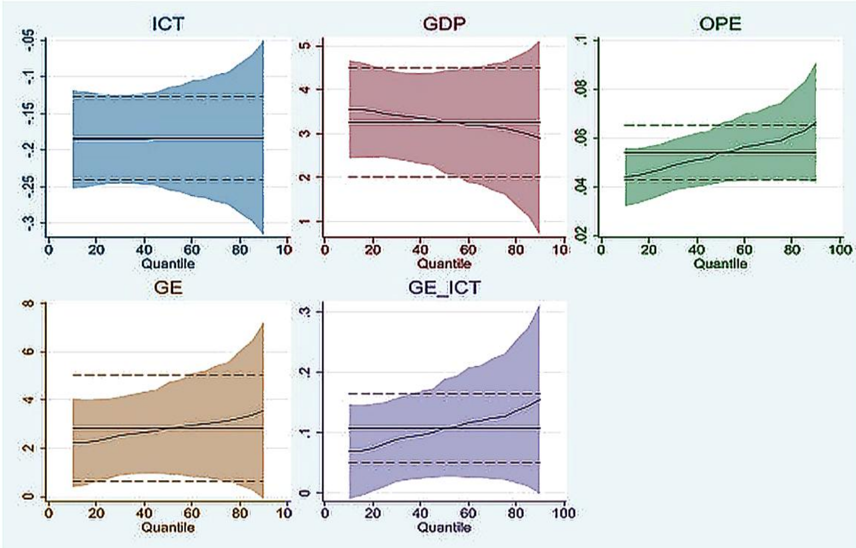

Figure 3. MMQR Model-2 (*Source: Authors' estimations using Stata*)

Based on the MMQR estimates reported in Table 8 and illustrated in Figure 3, digital transformation (ICT) exerts a negative and statistically significant effect at the 1% level on consumption-based CO_2 emissions per capita across all quantiles, with relatively stable coefficients ranging from -0.185 (Q25) to -0.183 (Q90).

This finding confirms the emission-reducing role of ICT and is consistent with technology diffusion theory. The widespread adoption of digital technologies improves energy efficiency, optimizes production processes, and reduces resource waste. In the context of Southeast Asia, where rapid industrialization and digitalization coexist, ICT diffusion provides substantial potential for improving operational efficiency and mitigating emissions.

To better interpret this result, it is useful to compare it with existing literature. The evidence aligns with a growing body of literature suggesting that digital transformation contributes to environmental sustainability through improvements in energy efficiency, technological innovation, and resource optimization [30, 31]. Similar evidence has been documented in both cross-country and firm-level studies, where ICT adoption is found to reduce carbon emission intensity by enhancing production efficiency and enabling cleaner technologies [3, 4].

However, this result contrasts with studies that highlight the potential rebound effects of digitalization, whereby increased energy consumption from digital infrastructure, data centers, and expanded economic activity may offset environmental gains [4, 29]. These conflicting findings suggest that the environmental impact of digital transformation is not uniform but depends on structural conditions such as energy mix, level of economic development, and institutional quality.

In the context of Southeast Asian countries, the emission-reducing effect observed in this study may be explained by the relatively high marginal efficiency gains from digital adoption in developing economies, where production systems are still undergoing technological upgrading. At the same time, the weaker rebound effects compared to developed economies may reflect lower digital infrastructure intensity and energy demand from advanced digital services.

Nevertheless, the results should be interpreted with caution. While digital transformation appears to reduce emissions in this study, this effect may not be sustainable in the long run if digital expansion leads to increased electricity consumption without a corresponding transition toward renewable energy sources. Therefore, the environmental benefits of digital transformation are likely conditional rather than automatic, requiring complementary policies that promote green energy and sustainable digital infrastructure.

This implies that digital transformation alone is not a sufficient condition for environmental sustainability, but rather a facilitating factor whose effectiveness depends on broader structural and policy alignment. Importantly, this quantile-specific pattern suggests that the environmental benefits of digital transformation are more pronounced in high-emission contexts, where marginal efficiency gains are larger. This is consistent with the MMQR results, which show stronger emission-reducing effects at upper quantiles. However, this also implies that the estimated relationship may be sensitive to the distribution of emissions across countries, and caution is needed when generalizing these findings beyond the sample.

Beyond the direct effect of digital transformation, the moderating role of institutional quality provides further insights. Specifically, the interaction term GExICT is positive and statistically significant across all quantiles, increasing from 0.081 (Q25) to 0.157 (Q90), indicating that government effectiveness moderates the ICT-emissions nexus by weakening ICT's carbon-reducing effect, particularly in high-emission economies. From an institutional perspective, this suggests that governance structures and policy priorities shape how digital technologies are deployed. In many Southeast Asian countries, where development strategies remain growth-oriented and industrial expansion is prioritized, digital transformation may be primarily utilized to enhance productivity and scale up economic activity rather than to achieve environmental goals, thereby diluting its mitigation potential. Overall, the results imply that the environmental benefits of digitalization are not institution-neutral and can only be fully realized when digital strategies are aligned with explicit green governance and sustainability objectives. This also raises a potential concern that institutional effectiveness may not necessarily translate into environmental effectiveness if policy priorities remain growth-oriented, highlighting a possible trade-off between economic expansion and environmental sustainability. Accordingly, Hypothesis H2 is empirically supported, as government effectiveness weakens the emission-reducing effect of digital transformation on consumption-based CO_2 emissions per capita.

4.2. Robustness analysis

Table 9. BSQ Regression Model-1

Variables	Q25	Q50	Q75	Q90
ICT	-0.184*** (0.024)	-0.217*** (0.025)	-0.264*** (0.024)	-0.315*** (0.052)
GE	3.212*** (0.924)	3.997*** (0.952)	4.755*** (1.372)	6.096** (2.583)
GDP	2.242*** (0.610)	2.066*** (0.715)	2.283*** (0.755)	2.003 (1.707)
OPE	0.051*** (0.006)	0.062*** (0.006)	0.063*** (0.006)	0.069*** (0.015)
Constant	-19.251*** (4.992)	-17.362*** (5.733)	-17.147*** (6.546)	-13.932 (13.730)

*Note: Q25, Q50, Q75, and Q90 represent the 25th, 50th, 75th, and 90th conditional quantiles. The parentheses "()" show the standard errors. Asterisks *** and ** show significance levels at 1% and 5%.*

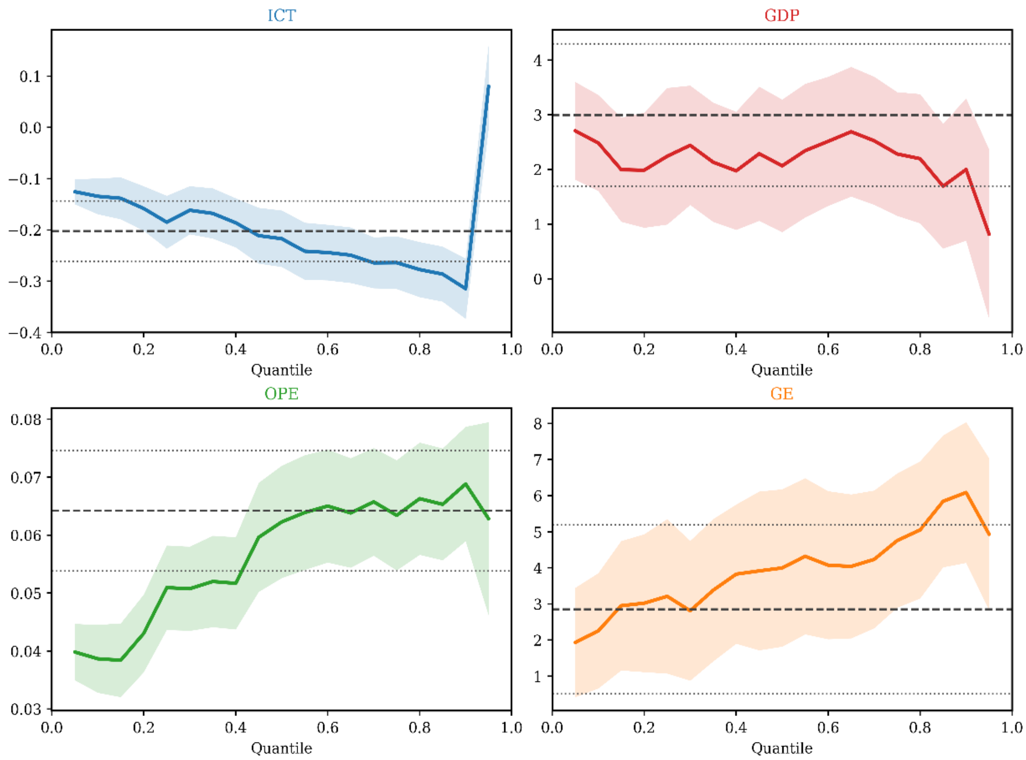

Figure 4. BSQ regression Model-1 (*Source: Authors' estimations using Stata*)

Table 10. BSQ Regression Model-2

Variables	Q25	Q50	Q75	Q90
ICT	-0.167*** (0.047)	-0.174*** (0.031)	-0.148** (0.077)	-0.146 (0.124)
GE	3.368*** (0.802)	4.059*** (1.149)	4.408*** (0.970)	5.938*** (2.166)
GExICT	0.100*** (0.034)	0.099*** (0.034)	0.128* (0.079)	0.242** (0.09)
GDP	2.607*** (0.455)	2.355*** (0.799)	2.307*** (0.592)	1.280 (1.110)
OPE	0.042*** (0.009)	0.048*** (0.005)	0.048*** (0.012)	0.058*** (0.018)
Constant	-21.977*** (3.893)	-19.366*** (6.431)	-18.710*** (4.941)	-10.864 (9.792)

*Note: Q25, Q50, Q75, and Q90 represent the 25th, 50th, 75th, and 90th conditional quantiles. The parentheses "()" show the standard errors. Asterisks ***, ** and * show significance levels at 1%, 5% and 10%.*

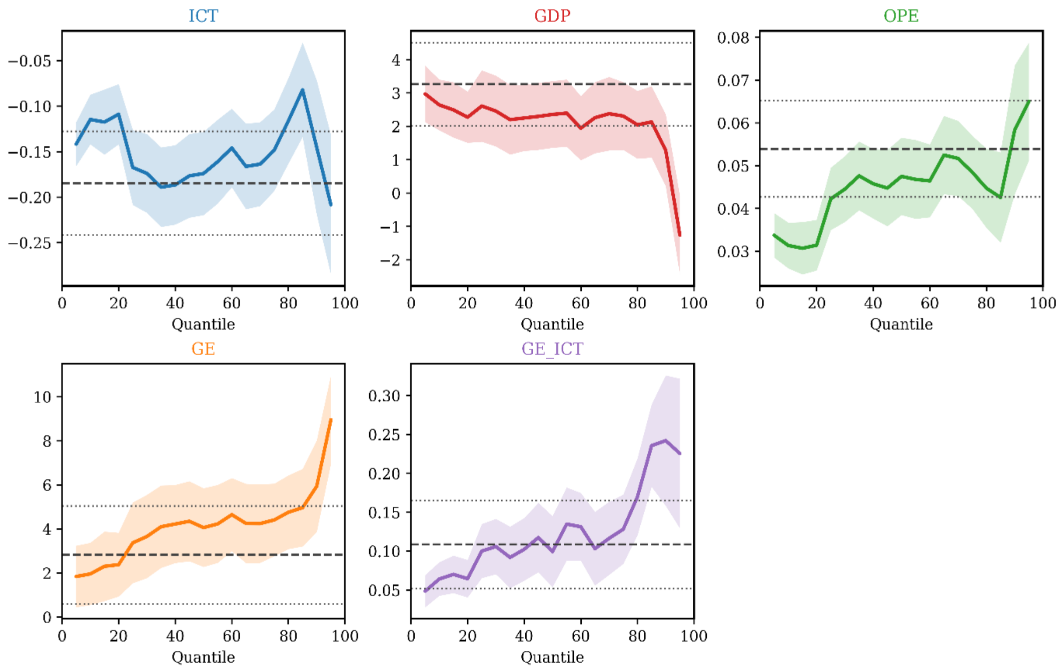

Figure 5. BSQ regression Model-2 (*Source: Authors' estimations using Stata*)

To ensure robustness, this study applies the BSQ regression. The results for Model 1, reported in Table 9 and Figure 4, confirm the MMQR findings, showing that ICT remains negative and statistically significant across all quantiles, while GE, GDP, and OPE exhibit positive and significant effects on consumption-based CO_2 emissions. Overall, the BSQ estimates display consistent quantile patterns, supporting the reliability of the baseline results.

The moderating effects in Model 2 are further validated using the BSQ regression. As reported in Table 10 and Figure 5, ICT remains negative and statistically significant at lower and middle quantiles, though its effect weakens at higher quantiles. More importantly, the interaction term GExICT is positive and significant across most quantiles, with stronger effects at upper quantiles, indicating that government effectiveness consistently weakens the emission-reducing role of ICT. Overall, the BSQ results confirm the robustness of the MMQR findings.

5. CONCLUSION AND RECOMMENDATIONS

Based on the empirical findings discussed above, several key conclusions can be drawn. The results indicate that digital transformation contributes to reducing consumption-based CO_2 emissions per capita in Southeast Asian countries over the period 2002-2022, thereby supporting Hypothesis H1. This emission-mitigating effect is statistically significant across all quantiles and becomes stronger at higher emission levels, suggesting a non-linear and heterogeneous impact with more pronounced environmental benefits in carbon-intensive economies. This finding is consistent with prior studies highlighting the role of digital transformation in improving energy efficiency and optimizing production processes [30-31].

These results can be explained through Rogers' Diffusion of Innovation theory [26], which emphasizes the role of technology adoption and diffusion as key transmission mechanisms. As digital technologies are gradually adopted and diffused across heterogeneous economic agents, they enhance operational efficiency, improve resource allocation, and facilitate the transition toward cleaner production processes. The extent of these environmental benefits depends on the depth and speed of technology adoption, which vary across countries and institutional contexts. This helps explain why the emission-reducing effects are stronger at higher emission levels, where the potential for efficiency gains and technological upgrading is greater.

However, when incorporating the moderating role of institutional quality, the interaction results reveal that government effectiveness weakens the emission-reducing impact of digital transformation, particularly at the upper quantiles, thereby supporting Hypothesis H2. This suggests that the diffusion of digital technologies is not institution-neutral but is shaped by policy priorities. In growth-oriented institutional environments, digital transformation may be directed toward expanding production scale rather than improving environmental performance, thereby offsetting its mitigation potential [44-46].

Overall, the findings highlight that the environmental impact of digital transformation operates through identifiable diffusion-based transmission mechanisms and is critically conditioned by institutional factors that influence the direction, intensity, and effectiveness of technology adoption.

Based on these findings, several targeted policy implications can be derived. First, given that the emission-reducing effect of digital transformation is stronger at higher emission quantiles, policymakers should prioritize the deployment of energy-efficient digital technologies in carbon-intensive sectors such as manufacturing, energy, and transport. This targeted approach can maximize the environmental benefits of digital transformation where mitigation potential is greatest.

Second, the moderating role of government effectiveness suggests that digital transformation in Southeast Asia is often oriented toward productivity expansion rather than environmental objectives. Therefore, governments should explicitly align digitalization strategies with environmental goals by integrating carbon reduction targets, green standards, and sustainability criteria into national digital policies and digital infrastructure investments.

Third, regulatory frameworks should be strengthened to ensure that digital expansion does not lead to rebound effects. This includes implementing environmental regulations for data centers, promoting green ICT standards, and providing incentives for firms to adopt low-carbon digital innovations.

Finally, enhancing regional cooperation within ASEAN is essential to address cross-country disparities in digital readiness and institutional quality. Coordinated policies, technology transfer, and joint green digital initiatives can help amplify the emission-reducing effects of digital transformation across the region.

Despite its contributions, this study has several limitations. First, the analysis is restricted to Southeast Asian countries, which may limit the generalizability of the findings to other regions with different institutional and economic contexts. Second, the proxy for digital transformation may not fully capture the multidimensional nature of digital transformation, particularly emerging technologies such as artificial intelligence and platform-based innovations. Third, while the MMQR approach captures distributional heterogeneity, it does not explicitly address potential endogeneity issues or dynamic adjustments among variables. Future research could extend this analysis by incorporating alternative digitalization indicators, applying dynamic panel techniques, and exploring causal mechanisms across different regional contexts.

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