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Pathways to Green Growth: Unveiling the Roles of Institutional Quality, Information and Communication Technology Diffusion, and Trade Integration

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ABSTRACT

This study investigates the impacts of institutional quality, Information and Communication Technology (ICT) diffusion, and trade openness on green growth in 21 countries from 2000 to 2019, using FMOLS, DOLS, quantile regression, and Dumitrescu–Hurlin causality tests. Results show that institutional quality consistently and significantly fosters green growth, while ICT diffusion and trade openness impose adverse effects. Efficiency gains from ICT trigger a rebound effect, thus undermining sustainability. Quantile regressions indicate that institutional quality benefits economies at lower quantiles but diminishes at higher ones; ICT negatively affects lower and median quantiles; and trade openness is largely detrimental except at the lowest quantile. Causality analysis reveals unidirectional effects from institutional quality and trade openness to green growth, while ICT and green growth share bidirectional feedback. Overall, policy solutions should strengthen governance, manage ICT rebound effects, and integrate environmental objectives into trade.

Keywords: Green Growth, Institutional Quality, Information and Communication Technology Diffusion, Trade Integration
JEL Classifications: O3, Q5, F4, C2

1. INTRODUCTION

The notion of "green growth" has transitioned from a widely embraced slogan to a fundamental policy objective (Suter et al., 2025). Green growth is established as an economic growth paradigm within the context of sustainable development, emphasizing the necessity to mitigate environmental damage while promoting economic advancement (Yang et al., 2025). Nonetheless, the methods to attain this goal continue to be contentious, especially in developing nations where industrial growth frequently results in environmental deterioration (Ahmed et al., 2022). Green growth fundamentally enhances traditional economic growth by integrating environmental sustainability and human development - elements frequently overlooked by standard growth metrics (Melnyk et al., 2020). Comprehending the factors that propel this expansive, inclusive advancement is particularly crucial for nations experiencing urbanization, digital change, and enhanced integration into the global economy (Khan et al., 2023; Prabhakar, 2025).

Three principal forces are pivotal in contemporary discussions on sustainability. The initial factor is the swift proliferation of information and communication technologies (ICT), which possess the capacity to diminish material consumption via dematerialization and enhanced resource efficiency (Boukhris et al., 2025; Ren et al., 2022). Nonetheless, this advantage is mitigated by the escalating demand for energy-intensive equipment and the onset of rebound effects that might substantially elevate total consumption (Peng and Qin, 2024). The second critical issue is the quality of institutions, characterized by active citizen engagement, contract enforcement, and anti-corruption measures, which have demonstrated the ability to foster cleaner production techniques and more equitable economic growth across various areas and income levels (Andabayeva et al., 2025; Riti et al., 2021). The third component, trade openness, reveals a more equivocal scenario. Liberalized commerce may promote the dissemination of eco-friendly technologies (Osman, 2025; Wen and Zhou, 2025). However, it can also encourage pollution-intensive sectors to move to nations with lax environmental regulations (Abid and Sekrafi, 2021).

Although each strand of literature covering digitalization, institutional quality, and trade openness offers substantial insights on its own, these drivers are rarely explored in an integrated framework. Most studies tend to isolate their effects, overlooking the potential interdependencies and combined influence these factors may exert on ecological outcomes (Ulhaq and Purwanto, 2023). This gap is especially pronounced in the context of interaction between technological advancement, governance capacity, and global economic integration in shaping sustainable development trajectories (Islam, 2025). As countries undergo rapid industrialization and institutional transformation, understanding how these forces collectively impact environmental performance becomes not only timely but essential (Fiorino, 2011). However, empirical research that simultaneously captures this complex dynamic remains limited, leaving policymakers without comprehensive evidence to design effective, context-sensitive sustainability strategies.

Keyword co-occurrence analyses in Figures 1-3 demonstrate a fragmented green growth and primary variables research environment. The first network addresses corruption, financial development, renewable energy use, and institutional quality as governance anchors for carbon emissions, economic growth, and trade openness. However, green growth research has few ICT ties, indicating limited digital governance. In the second network, trade openness is linked to economic growth, carbon emissions, renewable energy, and green innovation, but governance and ICT are marginal, indicating that macroeconomic or energy-trade frameworks neglect institutional or technological facilitators. ICT links economic growth, carbon emissions, innovation, and renewable energy in the third network, demonstrating its technical significance in sustainability. Lack of governance terminology and incomplete trade integration suggest ICT's environmental impact is studied independently. These trends show that institutional quality, ICT penetration, and trade openness are rarely researched together in relation to green growth. To fill this gap, this research combines government, technology, and commerce. This triadic approach connects disciplinary silos and provides policy-relevant insights for coordinating institutional performance, digital transformation, and trade liberalization for sustainable and equitable green growth.

This study stimulates green growth literature four ways. Our empirical framework integrates institutional quality, ICT spread, and trade openness, unlike previous research that explored these green growth determinants separately. Integrative techniques show how governance quality affects digitalization and trade's environmental repercussions, which independent variables may miss. Assessing the aggregate impact of various components better models' policy contexts where improvements in one area can spillover into others. This synthesis identifies economic, social, and environmental sustainability measures. Second, PCA composited institutional quality and ICT diffusion. To reduce multicollinearity, retain idea depth, and better convey complexity, this method

Figure 1: Keyword co-occurrence analysis for the core nexus between green growth and institutional quality. 264 results from Web of Science Core Collection with the keywords: "green growth" and "institutional quality"

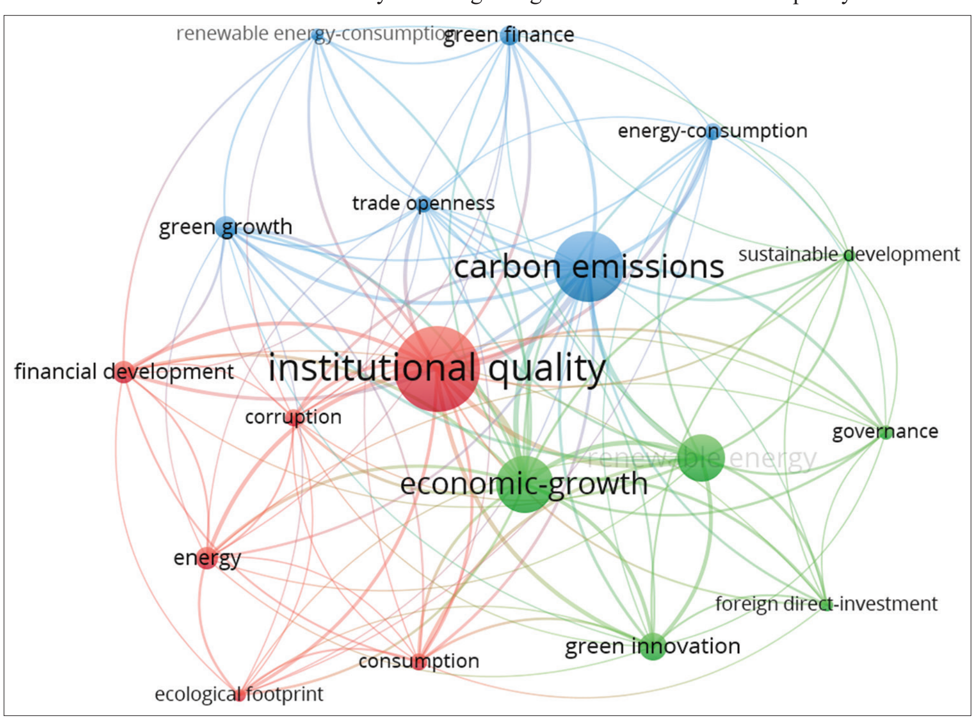


Figure 2: Keyword co-occurrence analysis for the core nexus between green growth and trade openness. 483 results from Web of Science Core Collection with keywords: "green growth" and "trade openness"

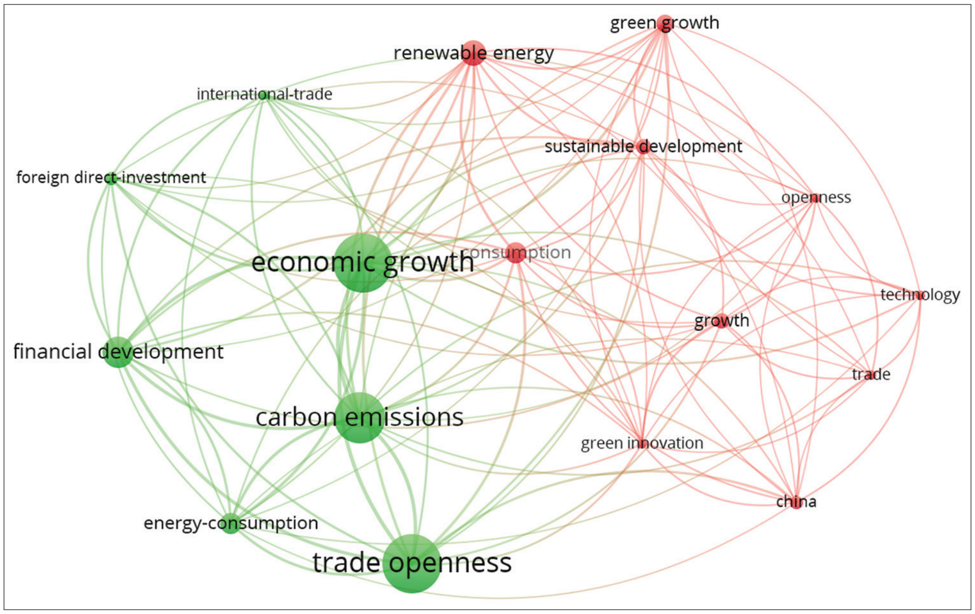
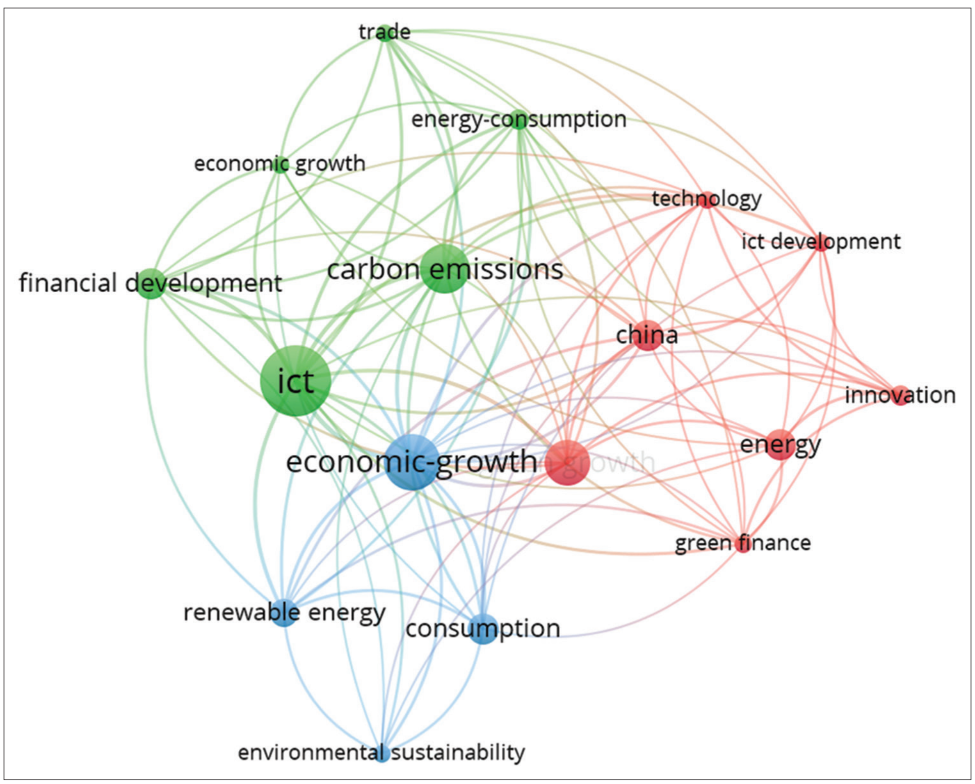


Figure 3: Keyword co-occurrence analysis for the core nexus between green growth and ICT. 278 results from Web of Science Core Collection with the keywords: "green growth" and "ICT"



combines several indications into two multidimensional assessments. PCA-based metrics cover governance and ICT aspects such rule of law, regulatory quality, infrastructure, and digital adoption. Empirical investigation uses statistically robust and conceptually thorough factors, making conclusions more reliable and interpretable. Third, the study improves procedure with quantitative evidence. Globalized economies' cross-sectional reliance is assessed using a second-generation unit root test (CIPS) to avoid bias from ignoring cross-country interconnections. Pedroni and Kao cointegration tests, FMOLS and DOLS long-run estimations, and quantile regression heterogeneous effect evaluation explain linkage distributional differences. Static estimates are dynamic in the Dumitrescu–Hurlin panel causality test due to changeable directionality and reciprocal reinforcement. Subsamples from high- and middle-income nations confirm and generalize the findings, preventing structural bias. The study concludes with realistic policy recommendations for developing nations. The findings identify governance thresholds, explain trade scenarios when openness supports environmental goals, and emphasize ICT's rebound effects to balance economic growth with environmental and social welfare. Governments use this information to construct integrated digital, institutional, and trade policies. The study offers an evidence-based paradigm for sustainable development in a digitalized, linked global economy, boosting academic discourse and policymaking.

The remainder of the paper is structured as follows: Section II reviews the relevant literature and theoretical foundations. Section III offers a detailed description of the data sample, variable definitions, econometric methodology, and the justification for the chosen analytical approach. Section IV reports and interprets empirical findings. Section V provides an in-depth discussion of these results. Finally, Section VI concludes the study and outlines policy recommendations derived from the empirical evidence

2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

2.1. Theoretical Framework

The theoretical basis of the connection between information and communication technologies (ICT) and green development is debated, with actual research yielding conflicting perspectives. Some researchers contend that the expansion of ICT may hinder green growth. This perspective highlights that the expansion of ICT results in heightened manufacturing of ICT devices, higher transportation requirements for these devices, broader utilization of ICT applications, and a rise in electronic trash (Danish, 2019; Houghton, 2015). The "rebound effect" hypothesis asserts that although ICT adoption improves manufacturing efficiency and lowers production costs, it concurrently increases demand for more affordable and efficient products, thus intensifying resource consumption and environmental strain (Nejati and Shah, 2023). Conversely, an expanding corpus of studies highlights the capacity of ICT to promote green growth. ICT applications may enhance environmental awareness, promote the implementation of novel green technologies, and assist in environmental monitoring and management (Yang and Sun, 2023). Furthermore, ICT-enabled networks promote the extensive dissemination of conservation knowledge (Iqbal et al., 2024; Qayyum et al., 2024) and contribute to the "dematerialization effect" - the shift from the physical distribution of goods to the delivery of digital services (Pettifor et al., 2024). This transition, bolstered by the extensive utilization of the internet and mobile technology, diminishes transportation requirements and greenhouse gas (GHG) emissions (Chatti, 2021). Moreover, ICT provides novel solutions for optimizing energy production, upgrading transportation systems, and advancing urban sustainability (Zhong et al., 2025).

A significant amount of scholarship highlights the crucial importance of institutional quality in influencing economic success and environmental sustainability. The quality of governance has been demonstrated to affect sustainable development outcomes via several mechanisms, such as effective policy formulation, regulatory implementation, and corruption mitigation. Ahmed et al. (2022) reveal that effective governance positively influences economic growth in South Asian countries, while Abdelbary and Benhin (2019) illustrate analogous advantages for economic development and human capital in Arab nations from 1995 to 2014. Samarasinghe (2018) emphasizes that a 1% enhancement in corruption prevention may result in a 6.9% increase in economic development. Furthermore, Dluhopolskyi et al. (2019) contend that governments that can effectively mobilize suitable institutional resources can improve environmental efficiency. In accordance with this, Azimi et al. (2023) and Garcia-Sanchez et al. (2013) demonstrate that good governance promotes fair and sustainable economic growth by enhancing environmental dependability. Halkos and Tzeremes (2014) demonstrate that public sector efficiency and corruption control directly affect environmental performance. Carlsson and Lundström (2001) provide empirical evidence of a positive correlation between governmental competence and environmental efficiency, whereas Bernauer and Koubi (2009) demonstrate that democratic governance can mitigate pollution levels. Baloch and Danish (2022) assert that robust governance substantially alleviates the effects of climate change in low- and lower-middle-income nations, principally evidenced by decreased CO_2 emissions, thereby promoting environmental sustainability.

In the last thirty years, the correlation between trade openness and economic development has undergone significant theoretical and empirical examination; however, the findings remain ambiguous (Keho, 2017). Pradhan et al. (2022) delineate three principal ways by which trade openness might stimulate economic growth. Initially, it can have a multiplier impact via enhanced international trade. Secondly, increased exports furnish nations with the foreign currency required for engaging in worldwide marketplaces and obtaining vital inputs for local industry. Third, export development allows economies to increase their market share, leverage economies of scale, and mitigate susceptibility to currency volatility and other market variations. Empirical investigations of the trade-growth relationship yield varied results. (Bahmani-Oskooee and Niroomand, 1999) and Zarra-Nezhad et al. (2014) establish a positive correlation between trade openness and economic growth, while Ulaşan (2015) finds no empirical evidence supporting the trade-led growth hypothesis. Rigobon and Rodrik (2005) indicate a substantial negative impact of trade openness on income levels, although Fenira (2015) characterizes the link as tenuous. Furthermore, Rassekh (2007) posits that low-income economies have higher advantages from trade compared to high-income ones.

2.2. Hypotheses Development

2.2.1. Information and communication technology and green growth

An empirical study on the complex interaction between ICT and green development enhances this discourse. Li and Zhang (2023) regard ICT and financial integration as essential accelerators for China's sustainable economic growth, but with inconsistent long-term impacts. Li et al. (2022) similarly illustrate that ICT has both immediate and enduring positive effects on green growth in China from 1995 to 2020. Usman et al. (2021) assert that in South Asia, whereas ICT adoption promotes economic growth, only India exhibits a consistent positive link between ICT and energy conservation, suggesting disparate outcomes among countries. Sun and Shi (2024) highlight the temporal variability of ICT's environmental impact, indicating that its effect on reducing CO_2 emissions increased from 1995 to 2004 but thereafter declined. Their findings imply that the utilization of ICT is more effective in diminishing emissions in high-income countries, indicating potential disparities between developed and developing economies. This study formulates the subsequent hypothesis to examine the impact of ICT in certain developing economies based on these insights:

H_1: ICT diffusion positively influences green growth.

2.2.2. Quality of institutions and green growth

Recent research reinforces the assertion that institutional quality is pivotal in promoting green economic growth. Azam et al. (2021) emphasize that efficient institutions establish the legal and regulatory frameworks essential for mitigating CO_2 emissions from economic activities, thereby fostering responsible and sustainable development. Obobisa et al. (2022) similarly demonstrate that institutional strength significantly impacts long-term economic development in three African emerging nations. Supporting these findings, Stoever (2012) and Ahmed et al. (2022) demonstrate that superior institutional quality in South Asian countries positively influences sustainable economic growth, since regional governments persistently endeavor to enhance environmental governance. These studies collectively provide a robust conceptual and empirical foundation for the notion that improved institutional quality increases the ability of economies, particularly in developing environments, to attain sustained and ecologically sustainable growth.

H_2: Institutional quality positively influences green growth.

2.2.3. Trade openness and green growth

In addition to its economic consequences, trade openness impacts environmental outcomes, which subsequently alter green development pathways. The theory of comparative advantage posits that increased trade liberalization can foster economic growth by allowing nations to specialize in commodities and services in which they possess a relative advantage (Essandoh et al., 2020). Nonetheless, the environmental impacts are complex. Conversely, lax environmental restrictions in certain nations may entice pollution-heavy companies, intensifying environmental deterioration. Conversely, commerce can enable the influx of eco-friendly technology and knowledge transfer, hence advancing cleaner manufacturing methods and environmental sustainability (Sarkodie and Strezov, 2019). The Heckscher–Ohlin paradigm suggests that trade openness is more significant for domestically scarce natural resources, but its effect is diminished for abundant resources (Khan et al., 2022; Le et al., 2016). The dual character of trade's impact highlights the necessity of policy formulation to guarantee that liberalization promotes both economic and environmental goals.

H_3: Trade liberalization positively influences green growth.

3. DATA AND MATERIAL

3.1. Data

This study employs panel data from selected nations over the period 2000-2019 to examine the influence of green growth, institutional quality, information and communication technology (ICT) diffusion, and trade openness on environmental quality through CO_2 emissions. The sample of this study comprises a balanced panel of 21 countries, classified according to the World Bank's income groupings into high-income countries (HICs) and middle-income countries (MICs). The HIC group includes Chile, Greece, Kuwait, Qatar, and Saudi Arabia. The MIC group consists of Brazil, China, Colombia, the Czech Republic, Egypt, Hungary, Indonesia, India, Mexico, Malaysia, Peru, the Philippines, Poland, Thailand, Türkiye, and South Africa. This selection captures a diverse set of economies across different regions, income levels, and development stages, allowing for a comprehensive analysis of the relationships among green growth, institutional quality, ICT diffusion, and trade openness across varying economic contexts.

After estimating the model for the entire dataset, the sample is divided into HICs and MICs to capture structural heterogeneity in the relationships under study. HICs and MICs differ greatly in economic, institutional, and technological features, which may affect estimated coefficient magnitude, direction, and significance. HICs have better infrastructure, institutional frameworks, and access to clean technology, which may affect how green growth, institutional quality, ICT diffusion, and trade openness affect environmental results. Resources, governance, and technology adoption limits may create different dynamics in MICs. Splitting the sample allows the analysis to identify income-specific effects, improve policy implications, and tailor recommendations to each group's developmental and structural realities rather than relying solely on aggregate results that may mask critical differences.

The availability of consistent data for the selected variables determines the study period. The selected economies are of particular interest due to their dynamic economic development, increasing integration into global trade, and growing emphasis on sustainable development policies. Data for the variables are primarily obtained from the World Development Indicators (WDI) and the Worldwide Governance Indicators (WGI), as well as authors' calculations where applicable.

3.2. Model Specification

The present study employs panel data econometric techniques to achieve its research objectives. Using panel data offers the advantage of a larger sample size, thereby enhancing statistical reliability and enabling more robust conclusions (Hassan et al., 2024). Moreover, panel datasets allow for the examination of dynamic effects across countries over time, capturing both cross-sectional and temporal variations. Such data structures provide richer variability, reduce multicollinearity, increase degrees of freedom, and yield more efficient estimations (Baltagi, 2008). Accordingly, the econometric framework developed in this study is designed to investigate the relationships between the selected explanatory variables—green growth, institutional quality, ICT diffusion, and trade openness - and the dependent variable. The model for the current research is as follows:

$$GRGR = f(INSQUA, ICT, TRADE) \quad (1)$$

$$GRGR_{it} = \beta_0 + \beta_1 INSQUA_{it} + \beta_2 ICT_{it} + \beta_3 TRADE_{it} + \mu_{it} \quad (2)$$

In the specified equation, the subscript i refers to the cross-sectional units (countries), while t denotes the time periods. The term β represents the parameter coefficients, and μ_{it} denotes the error term. In this study, green growth (*GRGR*) serve as the dependent variable, whereas the explanatory variables include institutional quality (*INSQUA*), information and communication technology (*ICT*), and trade openness (*TRADE*). Based on hypothesis development, the impacts of three variables of interest on green growth are expected to be positive $(\beta_1 = \frac{\partial GRGR}{\partial INSQUA} > 0, \beta_2 = \frac{\partial GRGR}{\partial ICT} > 0, \beta_3 = \frac{\partial GRGR}{\partial TRADE} > 0)$

Table 1 presents the detailed description and measurement of each variable.

Institutional Quality (INSQUA) reflects governance effectiveness and institutional robustness, constructed from six sub-components: voice and accountability, political stability with absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption. These sub-components are aggregated into a single index using component principal analysis (CPA). Data for institutional quality is sourced from the WGI database. Information and Communication Technology Diffusion (ICT) is computed through CPA using three indicators: mobile cellular subscriptions per 100 people, the proportion of individuals using the internet, and fixed broadband subscriptions per 100 people. This composite measure captures the extent of ICT penetration and digital infrastructure in each economy. Data are also obtained from the WDI and calculated by the authors.

Following the approach of Pradhan et al. (2014) and Appiah-Otoo and Song (2021) Component principal analysis (CPA) is applied to generate composite indices for both ICT diffusion and institutional quality. For ICT diffusion, the three widely used indicators - broadband subscriptions, mobile subscriptions, and internet usage—are incorporated. The institutional quality index uses six governance indicators: voice and accountability (VOA), political stability with no violence (PSNV), government effectiveness (GE), regulatory quality (RQ), rule of law (ROL), and corruption control. Panel A of Tables 2 and 3 reveals that PC1 explains 81.9% of ICT indicator variation and 77.9% of institutional quality indicator variation. In further regression analysis, ICT and INSQUA retain PC1 due to their high proportions. All three ICT variables - BROADBAND (0.565), MOBILE (0.548), and INTERNET (0.616) - have satisfactory coefficients under PC1, indicating that they are strong representatives of the ICT construct (Appiah-Otoo et al., 2023). For institutional quality, all six governance components have factor scores over 0.3 under PC1, ranging from 0.320 (VOA) to 0.438 (RQ), demonstrating their suitability for the composite INSQUA index. These findings support the use of CPA-derived PC1 scores as single composite measures for ICT diffusion and institutional quality in econometric calculations, retaining much of the datasets' variability while lowering dimensionality.

Trade Openness (TRADE) is expressed as the ratio of the sum of exports and imports to GDP, representing the degree of an economy's integration into global markets. Data for this measure are drawn from the WDI. The inclusion of these variables enables a comprehensive assessment of how economic, institutional, technological, and trade-related factors jointly shape environmental and developmental outcomes. Each variable is chosen to reflect a critical dimension of the study's focus on green growth and sustainable policy pathways.

3.3. Estimation Regression

3.3.1. Cross-sectional dependence (CDS) test

A proposal for the cross-sectional dependence test Pesaran (2021) is used with consideration of the following dynamics:

$$\Delta Y_{it} = \pi_i + Y_{i,t-1} + \gamma_i \xi_{it} + \sum_{j=1}^{p-1} \theta_i Y_{i,t-j} + \varepsilon_{it} \quad (3)$$

Table 1: Variable description

Variable	Explanation	Measurement	Source
GRGR	Green Growth	Green growth=GDPG+EDUCATION–FFC–NRP-CO_2E where GDPG is the annual growth rate of gross domestic product; EDUCATION stands for education expenditure divided by GDP; FFC is the ratio of fossil fuel consumption to total consumption; NRP is the money value of depleted minerals, including coal, crude oil, and natural gas; and CO_2E denotes the proportion of carbon dioxide emissions	WDI and the author's calculation
INSQUA	Institutional Quality	The current study employs six components, such as voice and accountability (VOA), political stability with no violence (PSNV), government effectiveness (GE), regulatory quality (RQ), rule of law (ROL), and control of corruption (CC), to account for institutional quality. These sub-items are integrated into a single composite index (INSQUA) based on component principal analysis (CPA)	WGI and author's calculation
ICT	Information and Communication Technology (ICT) diffusion	ICT is constructed by using CPA with three variables, such as mobile cellular subscriptions per 100 people (MOBILE), a proportion of individuals using the Internet of the population (INTERNET), and fixed broadband subscriptions per 100 people (BROADBAND)	WDI and the author' calculation
TRADE	Trade openness	The ratio of the summation of export and import volume to GDP	WDI

Source: Authors' synthesis and self-computation from the dataset of WDI and WGI. Green Growth (GRGR) is measured using a composite indicator calculated as GDP growth plus education expenditure share of GDP, minus fossil fuel consumption ratio, minus the monetary value of depleted natural resources, and the proportion of CO_2 emissions. This approach integrates economic performance with resource efficiency and environmental impact, making it a suitable proxy for sustainable growth. Data for this variable is sourced from the WDI and the author's computation

Table 2: Principal component analysis for ICT diffusion

Panel A: Explanation (%) for panel sample's variation of each component extracted			
Number	Value	Proportion	Cumulative proportion
PC1	2.458	0.819	0.819
PC2	0.438	0.146	0.965
PC3	0.104	0.035	1.000
Panel B: Scoring coefficients			
Variable	PC1	PC2	PC3
Broadband	0.565	−0.655	0.501
Mobile	0.548	0.752	0.365
Internet	0.616	−0.068	−0.784

Table 3: Component principal analysis for institutional quality

Panel A: Explanation (%) for panel sample's variation of each component extracted						
Number	Value	Proportion	Cumulative proportion			
PC1	4.675	0.779	0.779			
PC2	0.655	0.109	0.888			
PC3	0.278	0.046	0.935			
PC4	0.215	0.036	0.971			
PC5	0.097	0.016	0.987			
PC6	0.080	0.013	1.000			
Panel B: Scoring coefficients						
Variable	PC1	PC2	PC3	PC4	PC5	PC6
CC	0.425	−0.140	−0.325	−0.657	0.041	0.511
GE	0.411	−0.290	−0.346	0.727	0.135	0.282
PSNV	0.406	−0.175	0.850	0.047	−0.164	0.229
ROL	0.437	−0.249	0.030	−0.168	0.519	−0.670
RQ	0.438	0.175	−0.219	0.008	−0.763	−0.383
VOA	0.320	0.879	0.055	0.096	0.317	0.107

Where ξ_{it} it is a predetermined component. $\sum_{j=1}^{p-1}\theta_i Y_{i,t-j}$ is an Augmented Dickey Fuller (ADF) assessment. ε_{it} is cross-sectional for object i if and only if it shares similar characteristics.

$$\varepsilon_{it} = \theta_i f_t + u_{it} \tag{4}$$

Particularly, θ_i describes the unique effect of each i, so although u_{it} is a white noise with no cross-sectional or, alternatively, the individuals are not serially correlated. Incorporating Equation 2 into Equation 1 produces the subsequent expression:

$$\Delta Y_{it} = \pi_i + Y_{i,t-1} + \gamma_i \xi_{it} + \sum_{j=1}^{p-1}\theta_i Y_{i,t-j} + \theta_i f_t + u_{it} \tag{5}$$

Utilizing Pesaran (2007)'s procedure, a test of cross-section dependence analysis for object i and time t within a panel data, is performed with a null hypothesis (H_0: $\theta_i = 0$) and a substitute hypothesis (HA: $\theta_i = 0$). Table 4 reports the cross-sectional dependence tests for this study's panel data.

3.3.2. Unit root test

To examine the stationarity properties of the time series under consideration, unit root tests were applied. Given the presence of cross-sectional dependence in panels with a large number of

Table 4: Pairwise correlation

	GG2015	C1	TRADE	INS_QUALITY
GG2015	1			
ICT	−0.340	1		
TRADE	−0.233	0.332	1	
INS_QUALITY	−0.209	0.419	0.485	1

cross-sectional units (N) and relatively short time dimensions (T), Pesaran (2007)'s CIPS test was employed. The CIPS statistic is computed as:

$$CIPS = \frac{\sum_{j=1}^{N} CADF_j}{N} \tag{6}$$

The cross-sectionally augmented Dickey–Fuller statistic for unit j, denoted as $CADF_j$, is expressed as:

$$CADF_j = t_j(N,T) = \frac{\left(y_{j,-1}^T \bar{M} y_{j,-1}\right)^{-1}(y_{j,-1}^T \bar{M}\Delta y_{j,-1})}{\sqrt{\sigma_j^2 (y_{j,-1}^T \bar{M} y_{j,-1})^{-1}}} \tag{7}$$

Where $y_{j,-1} = (y_{j1},\ldots,y_{jT-1})^T$ denotes the lagged series, $\Delta y_j = (\Delta y_{j2},\ldots,\Delta y_{jT})^T$ represents the first differences, and $\sigma_j^2 = \frac{\sum_{t=1}^{T}\hat{\varepsilon}_{jt}^2}{T-4}$ with $\hat{\varepsilon}_{jt}^2 = \Delta y_{jt} - \Delta\hat{y}_{jt}$ being the residuals. The projection matrix $\bar{M}$ is defined as:

$$\bar{M} = I_T - \bar{H}(\bar{H}^T\bar{H})^{-1}\bar{H}^T \tag{8}$$

Where I_T is an identity matrix of order T x T and $\bar{H}$ is composed of artificial variables, including the cross-sectional averages of Δy_t and their lagged levels y_{t-1}. The asymptotic distribution of the CADF statistic differs from that of the standard ADF test due to the inclusion of cross-sectional dependence (Phillips and Sul, 2003). The critical values of the test are taken from the tabulations of Shariff and Hamzah (2015).

3.3.3. FMOLS and DOLS estimation

The FMOLS and DOLS methods are beneficial for resolving the autocorrelation problem, particularly for panel data with a lengthy time span. The primary distinction between the two is the adjustment procedure for serial correlation errors. In contrast to the FMOLS, which uses the Newey-West estimator to correct the autocorrelation problem in the residuals u_{it}, the DOLS uses the lag and lead variables to accomplish the identical goal. The FMOLS coefficients following revision of conventional OLS are computed as follows:

$$\hat{\beta}_{FMOLS} = \left(\sum_{i=1}^{N}\hat{L}_{22i}^{-1}\sum_{t=1}^{T}\left(X_{it}-\bar{X}_i\right)^2\right)^{-1} \sum_{i=1}^{N}\hat{L}_{11i}^{-1}\hat{L}_{22i}^{-1}\sum_{t=1}^{T}\left(X_{it}-\bar{X}_i\right)Y_{it}^{*} - T\hat{\delta}_i \tag{9}$$

The assessment with the dependent variable and the independent variable is subsequently described as follows:

$$Y_{it}^{*} = \left(Y_{it} - \bar{Y}_i\right) - \left(\frac{\hat{L}_{21i}}{\hat{L}_{22i}}\right)\Delta X_{it} + \left(\frac{\hat{L}_{21i}-\hat{L}_{22i}}{\hat{L}_{22i}}\right)\beta\left(X_{it}-\bar{X}_i\right) \qquad (10)$$

$\hat{\delta}_i$ in Equation 3 can be denoted as follows:

$$\hat{\delta}_i \equiv \hat{\Gamma}_{21i} + \hat{\Omega}_{21i}^{0} - \left(\frac{\hat{L}_{21i}}{\hat{L}_{22i}}\right)\left(\hat{\Gamma}_{22i} + \hat{\Omega}_{22i}^{0}\right) \qquad (11)$$

In Equation 6, the symbols Ω, Γ, and L stand for the asymptotic covariance matrix for variance in the long term, respectively. The assessment of FMOLS is performed using this method with two prominent advantages. Initially, FMOLS produces specific regression intercepts. Second, FMOLS assists in correcting the autocorrelation qualities of panel data objects.

The DOLS model is based on a seminal study by Kao and Chiang (2001). The model description is as follows:

$$Y_{it} = \beta_i^{'} x_{it} + \sum_{i=-q}^{q} \zeta_{ij}\Delta X_{i,t+j} + \gamma_{1i}^{'} D_{1i} + \varepsilon_{it} \qquad (12)$$

In Equation 7, the symbol q indicates the quantity of estimation lags or leads. Adjusting capacity for impartial estimation is the primary distinction between the FMOLS and DOLS. By utilizing lags and leads via parameter *q*, the DOLS is superior at handling endogeneity or co-integrated variable issues (Westerlund, 2005). DOLS can assist in handling endogeneity error, according to an alternative explanation. In this study, both assessments are done as a means of evaluation.

3.3.4. Quantile regression

Most research on elements and carbon dioxide emissions uses the usual OLS method. However, the above method just provides the contingent anticipation (average value) of the dependent variable and does not explain the conditional distribution. Due to heterogeneity in emerging countries, technical improvements, trade openness, institutional quality, and green growth may vary between polluters with varying green growth levels. Quantile regression allows coefficients to change between quantiles. It can distinguish the effects of scientific progress, trade openness, and institutional quality on green growth distribution. Quantile regression can also address heteroscedasticity, anomalies, and undetected heterogeneity, which can reduce estimate precision. This study employs quantile regression to completely explore the relationships between ICT, trade openness, and institutional quality and green growth at different quantiles. The following econometric model covers panel data conditional quantile function:

$$Q_{y_{it}}\left(\tau x_{it}\right) = x_{it}^{'}\beta\left(\tau\right) + \alpha_i + \varepsilon_{it} \qquad (13)$$

In Equation 8, $Q_{y_{it}}\left(\tau x_{it}\right)$ represents the τ-th quantile of the dependent variable, x_{it} corresponds to a vector of explanatory variables, and α_i represents an individual impact. τ indicates the quantile; $\beta(\tau)$ is the regression parameter of the τ^{th} quantile, which can be calculated using the equation below:

$$\beta\left(\tau\right) = \underset{\beta(\tau)}{argmin} \sum_{k=1}^{q}\sum_{t=1}^{T}\sum_{i=1}^{N}\left(\left|y_{it} - \alpha_i - x_{it}^{'}\beta\left(\tau\right)\right| W_{it}\right) \qquad (14)$$

In Equation 9, *q* represents the quantity of quantiles. *T* defines the quantity of years, and *N* stands for the quantity of sample countries. W_{it} is the weight that is placed on the *t*th country in the *t*th year, which is in line with the individually linear quantile loss function suggested by Koenker and Bassett Jr (1978). The definition of weight is:

In the condition of $y_{it} - \alpha_i - x_{it}^{'}\beta\left(\tau\right) < 0$, the consequence is $W_{it} = \tau$

In the condition of $y_{it} - \alpha_i - x_{it}^{'}\beta\left(\tau\right) > 0$, the consequence is W_{it} = 1-τ

The present work implements the methodology of Koenker (2005) by employing Tukey's trimean as an example and establishing 0.25, 0.50, 0.75, and 0.9 accordingly to τ or the quartile.

3.3.5. Panel causality tests

To determine the causal connections between the relevant variables, Dumitrescu-Hurlin causality tests for panel data are applied. This method is an improved version of the well-known Granger noncausality assessment for panel data. The Dumitrescu-Hurlin test includes two distinct figures: Wbar-statistics (for calculating average figures) and Zbar-statistics (for depicting a conventional normal distribution) (Dumitrescu and Hurlin, 2012). Both values show disapproval of the null assumption and absence of causality, in addition to three possibilities: either two variables have unilateral causality, bi-directional causality exists between them, or there does not exist a causal relationship (Zeren and Ari, 2013).

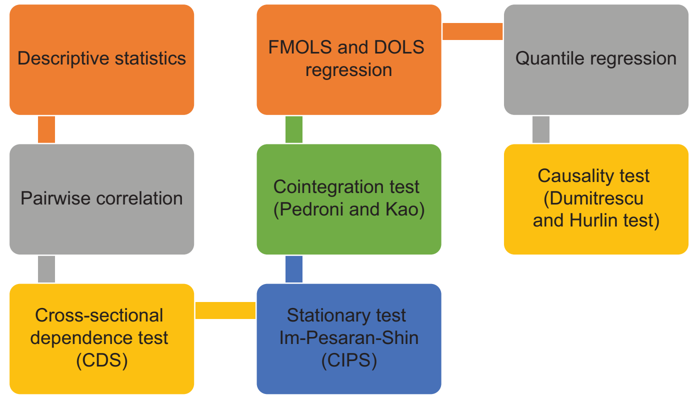
The empirical estimation framework is depicted in Figure 4 and consists of sequential steps, which are described in detail in the following sections.

4. RESULTS AND DISCUSSION

4.1. Descriptive Statistics

In Table 5, descriptive statistics demonstrate the primary variables' distribution and variability. For Green Growth (GRGR), the mean value is −73.1, with a narrow SD of 12.8, ranging from −97.4 to −40.5. The Jarque–Bera (JB) test (P = 0.001) rejects a normal distribution despite skewness (0.4) and kurtosis (2.3). INSQUA

Figure 4: Flowchart of the applied analysis



calculates institutional quality using six governance measures: VOA, PSNV, GE, RQ, ROL, and CC. These components' low averages and moderate variability (SD 0.3-0.9) imply normalized governance scores. Many components exhibit skewness near zero and kurtosis around 2-3, but all fail the normalcy test (JB P < 0.05), indicating non-normal governance measures. Broadband, mobile, and ICT distribution vary widely per country. For broadband, the mean is 7.7 subscribers per 100 people, ranging from 0 to 35, with positive skewness (1.2). Mobile penetration is high (mean 90.4, median 98.6) with large dispersion (SD = 44.6) and slight negative skewness. Digital divide: 38.2% internet usage, 0.6-95.7% range. All ICT indices are non-normal. Trade openness (TRADE) averages 77.9% of GDP and ranges from 22.1% to 220.4% with a high SD of 43.5. Positive skewness (1.1) and kurtosis (3.3) indicate a right-tailed distribution, and the JB test confirms non-normality (P < 0.001). Higher cross-country variance, positive skewness, and deviations from normality in the four primary variables and their components justify non-normal distribution-resistant econometric approaches.

Furthermore, the pairwise correlation matrix in Table 4 reveals statistically significant associations among the variables used in this study. Specifically, all explanatory variables—green growth (GRGR), institutional quality (INSQUA), ICT diffusion, and trade openness—display meaningful correlations with the dependent variable. The direction and magnitude of these correlations suggest that environmental outcomes are closely connected to economic performance, governance quality, technological advancement, and trade integration. These results provide a preliminary indication of interdependence among the variables and justify further investigation into their long-run relationships through cointegration analysis.

4.2. Cross-sectional Dependence

The use of macroeconomic indicators can lead to a non-stationary phenomenon. To prevent a potential issue of spurious regression, it is ensured that the studied variables are not integrated at I(2). Cross-sectional dependence is employed to confirm the variables' stationarity as reported in Table 6. The findings reveal that all variables are integrated at I(1) for both trend and non-trend features.

4.3. Stationary Tests

Utilizing stationarity testing suggested by Im et al. (2003) and Levin et al. (2002) in addition to the Pesaran panel unit root test in the presence of cross-section dependence established by Pesaran (2007), stationary tests are used to confirm the possibilities of the spurious regression issue. Table 7 reports the results of the CIPS unit root test, accounting for cross-sectional dependence. The findings indicate that all variables—GRGR, INSQUA, ICT, and TRADE - are non-stationary at the level but become stationary after first-differencing under both constant and constant–trend specifications. Thus, all series are integrated of order one, I(1), at conventional significance levels.

4.4. Cointegration Test

Given that the unit root tests (CIPS) confirm all variables are integrated of order one, I(1), it becomes essential to assess whether

Table 5: Descriptive statistics

Variables	Mean	Median	Max	Min	SD	Skewness	Kurtosis	J-Bera	Prob.
GRGR	−73.1	−74.0	−40.5	−97.4	12.8	0.4	2.3	14.6	0.001
BROADBAND	7.7	4.4	35.0	0.0	8.2	1.2	3.8	84.6	0.000
MOBILE	90.4	98.6	191.0	1.7	44.6	−0.3	2.2	11.3	0.004
INTERNET	38.2	37.2	95.7	0.6	24.3	0.2	2.0	15.8	0.000
CC	−0.1	−0.2	1.5	−1.1	0.6	0.9	3.6	44.6	0.000
GE	0.2	0.2	1.3	−0.8	0.5	0.3	2.1	15.1	0.001
PSNV	−0.3	−0.4	1.3	−2.4	0.8	−0.1	2.3	6.6	0.036
ROL	0.0	−0.1	1.3	−0.9	0.6	0.6	2.2	26.4	0.000
RQ	0.3	0.2	1.5	−0.9	0.6	0.3	2.4	8.8	0.012
VOA	0.0	0.1	1.3	−1.9	0.9	−0.6	2.4	24.0	0.000
TRADE	77.9	62.2	220.4	22.1	43.5	1.1	3.3	57.7	0.000

Table 6: Tests of cross-sectional dependence

Variables	Breusch-Pagan LM	Pesaran scaled LM	Pesaran CD	Conclusion
GRGR	653.08***	34.41***	10.01***	Confirming the presence of cross-sectional dependence
INSQUA	839.89***	46.47***	-1.639*	Confirming the presence of cross-sectional dependence
ICT	2205.59***	134.62***	46.94***	Confirming the presence of cross-sectional dependence
TRADE	676.49***	35.92***	6.65***	Confirming the presence of cross-sectional dependence

***, **, and *denotes the statistical significance at 1%, 5%, and 10%, respectively

Table 7: Unit root test based on cross-sectional dependence Im-Pesaran-Shin (CIPS)

Variables	Level		First-difference		Order of Integration
	Constant	Constant and Trend	Constant	Constant and Trend	
GRGR	−1.649	−1.885	−2.501**	−3.188***	I (1)
INSQUA	−1.647	−1.914	−3.335***	−4.620***	I (1)
ICT	−1.984	−2.015	−2.330**	−2.607***	I (1)
TRADE	−1.251	−2.017	−2.398**	−3.294***	I (1)

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

these non-stationary series move together over time through a cointegration test, thereby avoiding spurious regression results. In order to offer the analysis of long-run relationships among variables, Pedroni (1999) test is employed to confirm or reject the null hypothesis of the absence of panel cointegration among variables. Table 8 reports the rejection of this null hypothesis for the majority of test statistics at 1% significance level, showing that there is the presence of long-term equilibrium linkage among the variables. To robust this finding, Kao (1999) is also used and it is observed in Table 9 that the null hypothesis of no cointegration is again rejected at 1% significance level. Therefore, it is evident that there is a long-run relationship among GRGR, INSQUA, ICT, and TRADE.

Applying Pedroni and Kao panel cointegration tests to the full sample provides a general understanding of the long-run linkages among green growth, institutional quality, ICT diffusion, and trade openness. Additionally, conducting tests separately for HICs and MICs enables the identification of potential income-specific cointegration patterns, acknowledging that economic structures, governance systems, and technology adoption levels may cause differences in the persistence and nature of these long-run relationships. This approach ensures that subsequent long-run estimations and policy recommendations are tailored to the developmental realities of each income group. As reported in Tables 10 and 11, it is evident that a stable long-run relationship exists among GRGR, INSQUA, ICT, and TRADE within both the HIC and MIC subsamples, thereby reinforcing the robustness and generalizability of the overall findings for the full sample.

Table 8: Pedroni (1999) cointegration

Criteria	Statistic	Prob.
Within-dimension		
Panel v-Statistic	−0.137	(0.554)
Panel rho-Statistic	−0.056	(0.478)
Panel PP-Statistic	−4.724***	(0.000)
Panel ADF-Statistic	−3.964***	(0.000)
Between-dimension		
Criteria	**Statistic**	**Prob.**
Group rho-Statistic	0.978	(0.836)
Group PP-Statistic	−7.197***	(0.000)
Group ADF-Statistic	−3.800***	(0.000)

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

Table 9: Kao (1999) cointegration

Criteria	t-Statistic	Prob.
ADF	2.699***	(0.004)
Residual variance	8.660	
HAC variance	6.571	

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

Table 10: Pedroni (1999) cointegration for separate samples of MIC and HIC

Country category	MIC		HIC	
Alternative hypothesis: common AR coefs. (within-dimension)				
Criteria	**Statistic**	**Prob.**	**Statistic**	**Prob.**
Panel v-Statistic	0.009	(0.666)	0.027	(0.582)
Panel rho-Statistic	0.654	(0.604)	−1.619	(0.118)
Panel PP-Statistic	−0.956***	(0.005)	−4.815***	(0.000)
Panel ADF-Statistic	−1.432***	(0.001)	−2.093***	(0.000)
Alternative hypothesis: individual AR coefs. (between-dimension)				
Criteria	**Statistic**	**Prob.**	**Statistic**	**Prob.**
Group rho-Statistic	1.288	(0.901)	−0.244	(0.404)
Group PP-Statistic	−4.040***	(0.000)	−5.454***	(0.000)
Group ADF-Statistic	−3.963***	(0.000)	−3.443***	(0.000)

4.5. FMOLS and DOLS Regression Results

Table 12 displays the regression findings of the FMOLS and DOLS methods to evaluate the study's principal findings. At the 1% significance level, the outcomes for institutional quality, ICT diffusion, and trade openness are also substantial. The findings do not support the first hypothesis and corroborate the existence of a significant negative long-term relationship between ICT diffusion and green growth in developing nations. This indicates that a 1% increase in ICT diffusion (as measured by the number of internet, broadband, and mobile phone users over 100 people) can inhibit sustainable growth by 4.72% and 9.87% in the FMOLS and DOLS results, respectively. The results align with prior studies (Shariff and Hamzah, 2015), indicating that increasing ICT diffusion can lower manufacturing costs and, consequently, product prices, primarily through the large-scale production of ICT equipment and the widespread application of ICT solutions. However, this cost reduction can trigger a "rebound effect" (Nejati and Shah, 2023), where lower prices stimulate greater consumption and production, ultimately leading to increased resource use and emissions. Such rebound effects can undermine the progress toward a sustainable economy (Sana et al., 2021).

In contrast, the findings validate the second hypothesis and prove the existence of a significant positive long-term relationship between institutional quality and green development in the sample countries. Green growth is positively driven by 4.182% (FMOLS) and 14.797% (DOLS) increase in institutional quality. This implies that as institutional quality improves, green growth is going to rise. One might contend that good governance has positive effects on the growth of human resources and the economy as a whole. The outcome is consistent with the importance placed on institutional quality, as it offers legislation to help in the reduction of carbon emissions Azam et al. (2021). This research concurs with Azam et al. (2021) conclusion that the institutional quality can organize

Table 11: Kao (1999) Cointegration for separate samples of MIC and HIC

Country category	MIC		HIC	
ADF	2.441***	(0.007)	−3.119***	(0.001)
Residual variance	7.307		10.015	
HAC variance	5.146		8.502	

Table 12: FMOLS and DOLS regression (Y=GRGR)

Variable	FMOLS		DOLS	
	Coefficient	**Prob.**	**Coefficient**	**Prob.**
INSQUA	4.182**	(0.024)	14.797***	(0.003)
ICT	−4.718***	(0.000)	−9.870***	(0.000)
TRADE	−0.845***	(0.000)	−0.463***	(0.009)

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

the appropriate forces to enhance economic growth along with environmental efficiency.

Studies corroborate a significant adverse long-term association between trade openness and green growth in emerging nations, refuting the third hypothesis. Therefore, a 0.845% (FMOLS) or 0.463% (DOLS) rise in trade openness results in a 1% reduction in green growth. It can be claimed that trade deregulation can contribute to a relaxation of environmental laws and regulations, making developing nations desirable locations for pollution-intensive manufacturing businesses (Essandoh et al., 2020). In the present research, lax restrictions on the working conditions of employees in emerging countries serve as a red flag for the green and sustainable development of emerging nations (Houssam et al., 2023).

Table 13 reports the FMOLS and DOLS results for high-income (HIC) and middle-income (MIC) countries. All three explanatory variables display consistent signs and strong statistical significance across both subsamples. Institutional quality (INSQUA) is positive and significant at the 1% level, with coefficients ranging from 3.37% to 7.83%, indicating that stronger governance and regulatory effectiveness enhance the dependent variable. ICT diffusion exerts a negative and significant effect (−0.70-−7.72%), suggesting efficiency gains and sustainability improvements through reduced dependence on the outcome variable. Trade openness is also negative and highly significant (−0.47-−6.41%), reflecting the role of international integration in diffusing cleaner technologies and improved production standards. The stability of these results across income groups and estimation methods underscores the robustness of the relationships.

4.6. Quantile Regression Results

Table 14 displays the quantile regression findings, illustrating the varied impacts of institutional quality (INSQUA), ICT diffusion, and trade openness on GRGR over the conditional distribution. INSQUA has a substantial and statistically significant effect at lower quantiles (Q10 = 1.476%; Q25 = 1.981%), suggesting that institutional enhancements promote growth resilience in less robust economies. Nevertheless, beyond the median (Q50), the effect reduces and becomes insignificant or negative at higher quantiles (Q75 and Q90), indicating a declining or even detrimental influence on stronger performers. The diffusion of ICT demonstrates a persistently negative correlation with GRGR in the lower and median quantiles (−1.049-−1.444%), suggesting that digital adoption may improve efficiency and diminish dependence on resource-intensive growth. This effect, however, becomes insignificant in economies with higher growth rates. Trade openness exhibits a generally negative and significant correlation (−0.054-−0.075%) across the majority of quantiles, excluding Q10, indicating that increased trade integration typically reduces GRGR, with the impact most pronounced in middle- and high-performing economies due to technology transfer, efficiency improvements, and competitive pressures.

Table 15 presents quantile regression findings for MICs and HICs, emphasizing significant differences from the pooled sample. For MICs, institutional quality (INSQUA) is constantly positive and highly significant over quantiles, reaching its apex at Q50 (14.013%) and maintaining substantial values at Q75 (9.717%) and Q90 (6.467%). This highlights the importance of governance, rule of law, and regulatory efficacy in promoting green growth. In contrast, trade openness has a sustained negative impact (−1.825% at Q10-−0.535% at Q90), indicating reliance on resource-intensive exports. The adoption of ICT is consistently negative and significant, with the most pronounced impact at Q50 (−12.287%), indicating that efficiency improvements may be counterbalanced by increased energy or resource use. In high-income countries, the findings are more intricate. INSQUA is positively and significantly correlated at lower and median quantiles (Q10: 4.147%; Q25: 2.856%; Q50: 7.017%), but becomes negligible and negative at Q90 (−6.309%), suggesting a reduction or reversal of institutional advantages as green growth intensifies. Trade continues to exhibit a negative and substantial trend, albeit less pronounced than in MICs (−1.198% at Q10-−0.392% at Q90). The diffusion of ICT exhibits no substantial impact across any quantile, indicating saturation in developed economies. Overall, findings indicate context-specific determinants: in middle-income countries, institutions significantly bolster GRGR, whereas trade and ICT impede it; in high-income countries, institutional impacts

Table 13: Revisiting FMOLS and DOLS for separate samples of HIC and LIC

Variable	HIC				MIC			
	FMOLS		DOLS		FMOLS		DOLS	
	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
INSQUA	4.766***	(0.000)	7.832***	(0.003)	7.343***	(0.000)	3.373**	(0.039)
ICT	−0.777***	(0.000)	−7.722*	(0.080)	−0.730***	(0.000)	−0.753***	(0.000)
TRADE	−0.740***	(0.000)	−0.466***	(0.000)	−6.312**	(0.015)	−6.411***	(0.000)

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

Table 14: Quantile regression (Y=GRGR)

Variables	Q10	Q25	Q50	Q75	Q90
INSQUA	1.476***	1.981***	0.957	−0.968	−1.291
	(0.000)	(0.000)	(0.115)	(0.117)	(0.104)
ICT	−1.049**	−1.313**	−1.444*	−0.648	−0.556
	(0.010)	(0.012)	(0.066)	(0.417)	(0.588)
TRADE	−0.022	−0.054***	−0.054***	−0.071***	−0.075***
	(0.142)	(0.005)	(0.060)	(0.016)	(0.048)

***, **, and * denotes the statistical significance at 1%, 5%, and 10%, respectively

Table 15: Quantile regression for separate samples of MIC and HIC (Y=GRGR)

			MIC		
Variables	**Q10**	**Q25**	**Q50**	**Q75**	**Q90**
INSQUA	3.774**	4.936*	14.013***	9.717***	6.467***
	(0.022)	(0.086)	(0.000)	(0.000)	(0.000)
TRADE	−1.825***	−1.523***	−0.861***	−0.629***	−0.535***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ICT	−3.314**	−5.217***	−12.287***	−8.522**	−4.282**
	(0.011)	(0.005)	(0.000)	(0.020)	(0.033)
			HIC		
Variables	**Q10**	**Q25**	**Q50**	**Q75**	**Q90**
INSQUA	4.147***	2.856***	7.017***	8.719	−6.309
	(0.001)	(0.007)	(0.001)	(0.222)	(0.297)
TRADE	−1.198***	−0.999***	−0.667***	−0.550***	−0.392***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ICT	0.765	0.670	2.178	2.684	2.994
	(0.796)	(0.851)	(0.487)	(0.511)	(0.690)

Table 16: Causality results employing the Dumitrescu and Hurlin test

Null hypothesis	Zbar-Stat.	Prob.	Causality conclusion
INSQUAL→GRGR	4.336***	(0.000)	☒
GRGR→INSQUAL	0.927	(0.354)	
ICT→GRGR	5.461***	(0.000)	☑
GRGR→ICT	3.697***	(0.000)	
TRADE→GRGR	6.870***	(0.000)	☒
GRGR→TRADE	0.027	(0.978)	
ICT→INSQUAL	9.049***	(0.000)	☑
INSQUAL→ICT	1.981**	(0.048)	
TRADE→INSQUAL	2.522**	(0.012)	☑
INSQUA→TRADE	3.453***	(0.001)	
TRADE→ICT	3.062***	(0.002)	☑
ICT→TRADE	5.073***	(0.000)	

***, **, and * denote the statistical significance at 1%, 5%, and 10%, respectively

are conditional, trade is slightly adverse, and ICT is predominantly neutral. These disparities indicate that green growth plans must be sensitive to income and structure, utilizing institutional changes, suitable trade policies, and tailored ICT diffusion.

4.7. Dumitrescu-Hurlin Causality Tests

The Dumitrescu and Hurlin panel causality test results in Table 16 show several statistically significant causal relationships between green growth (GRGR), institutional quality (INSQUAL), ICT, and trade openness. First, institutional quality improves green growth (Zbar = 4.336, P = 0.000), while the reverse effect is statistically negligible. ICT has a bidirectional causal relationship with GRGR, with ICT promoting green growth and GRGR promoting further ICT adoption (Zbar = 5.461, P = 0.000). TRADE has a substantial unidirectional association with GRGR, with TRADE → GRGR (Zbar = 6.870, P = 0.000) being significant, but not the reverse GRGR → TRADE path. This suggests that trade openness may promote green growth, but not the other way around. Inter-variable dynamics show a bidirectional relationship between ICT and INSQUAL (Zbar = 9.049, P = 0.000; Zbar = 1.981, P = 0.048), indicating mutual reinforcement. Trade increases INSQUAL unidirectionally (Zbar = 2.522, P = 0.012), demonstrating that international standards and governance practices may improve institutional frameworks. Improvements in institutional quality can boost trade openness (Zbar = 3.453, P < 0.001). TRADE and ICT have a bidirectional association (TRADE → ICT: Zbar = 3.062, P = 0.002; ICT → TRADE: Zbar = 5.073, P = 0.000), indicating a synergistic relationship between global market integration and technical growth. The results show a complicated web of causal links, with ICT and INSQUAL driving green growth directly and indirectly through trade. This shows that coordinated policy efforts to improve institutional quality, technological diffusion, and trade openness may boost sustainable economic performance.

5. CONCLUSION

This study tackles the dearth of empirical research that simultaneously assesses the long-term effects of institutional quality, ICT spread, and trade openness on green growth across 21 nations from 2000 to 2019. Institutional quality has a positive long-term effect on green growth, but ICT diffusion and trade openness have negative effects. All FMOLS and DOLS calculations show institutional quality as a key factor of sustainability, but ICT and trade openness are long-term constraints. Quantile regression shows that institutional quality is most beneficial in countries with poor green growth performance, diminishing or reversing at higher levels, while ICT's negative effect is concentrated in the lower and median quantiles and disappears in higher-performing economies. Trade openness reduces green growth in most quantiles except the lowest (where it has no effect). Causality analysis shows that institutional quality and trade openness affect green growth unidirectionally, while ICT and green growth reinforce each other. All three drivers are interconnected, highlighting their complexity in sustaining economic performance.

The findings emphasize the necessity of enhancing institutional frameworks to promote green growth, especially in nations with subpar green growth performance, where governance enhancements produce the most significant benefits. Policymakers must tackle the rebound impacts of ICT proliferation by advocating for digital strategies that emphasize resource efficiency and low-carbon technologies. Trade policy must accord with environmental objectives by employing regulatory frameworks and environmental standards to prevent the relocation of pollution-intensive sectors. Considering the significant interdependencies identified in the causality study, comprehensive policy strategies that concurrently improve institutional quality, promote sustainable ICT use, and regulate trade openness are expected to yield synergistic advantages for green growth. The insights obtained from a balanced panel of 21 countries between 2000 and 2019 offer practical recommendations for attaining a sustainable growth trajectory while preserving environmental integrity.

This study utilizes a rigorous econometric methodology that addresses cross-sectional dependence, cointegration, and diverse effects within the green growth distribution; yet, several shortcomings persist. The composite indices for institutional quality and ICT dissemination, however comprehensive, may not entirely encompass all qualitative dimensions of governance and digitalization. Moreover, the emphasis on aggregate national statistics neglects possible subnational differences in the determinants of green growth. Future research may incorporate indices of environmental innovation, metrics for renewable energy deployment, and sector-specific trade patterns to enhance the comprehension of causative mechanisms. Extending the temporal framework or integrating non-linear dynamic models may elucidate threshold effects and enduring structural transformations.

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