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Digital economy-driven decarbonization pathways: analyzing how digital economy and globalization impact climate change in the top-10 digital economies

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In light of rising ecological challenges, the debate surrounding the digital economy and globalization in climate change has become prominent in formulating stringent environmental and sustainable policies. The current research debates environmental outcomes by analyzing the nexus between climate change, digital economy, globalization, industrial value addition, and urbanization in the top-10 digital economies. We use extensive empirical and econometric analysis to confirm the inverted U-shaped EKC hypothesis for gross domestic product and further report that the digital economy is integral to combating climate change. However, globalization, industrial value addition, and urbanization degrade ecological sustainability. Our strong theoretical and empirical analysis allows the current study to report novel policy suggestions aimed at promoting digital economic development and environmental sustainability.

KEYWORDS
climate change, digital economy, EKC hypothesis, globalization, sustainable development goals

1 Introduction

The growing environmental challenges from global warming have posed significant challenges to global compliance with sustainable development goals (SDGs) (Li et al., 2026). The rising industrial environmental footprint means that environmental policy intervention is necessary to avoid climate catastrophes (Jiang et al., 2023; Xu, 2025). However, despite rising emissions, global economies have been able to use "smart energy utilization" to yield higher GDP and achieve lower carbon intensity per unit of GDP. For example, China, despite rapid economic transformation, has significantly increased renewable energy (RE) capacity and lower carbon emissions by 1.4% per annum (World Bank, 2024). Such rapid improvements in energy intensity in industrial economies suggest positive environmental implications as energy efficiency improves environmental quality. These developments have encouraged policymakers and researchers to further comprehend how global economic policies align with energy policies.

Within the modern SDG context, the "digital economy" is essential to ecological sustainability. For example, a recent draft by the Ministry of Commerce, China, reveals that value addition from the digital economy in 47 industrial economies rose by 15.6% to reach US$ 38.1 trillion, equivalent to 45% of their GDP (World Bank, 2024). Among these, G20 economies account for about two-thirds of the global population, three-fourths of global trade, and 85% of global GDP, which has helped accelerate global digital and economic transformation. Additionally, digital transformation through policy adjustments, infrastructure construction, and digital value chains is key to reshaping the international policy adjustments and SDG compliance (Ma et al., 2024; Yang et al., 2024). Recent research shows that digital parameters influence all characteristics of modern life with human interactions, influencing business and economic models and even institutional policy-making (Bashir et al., 2024). For example, Kenya used mobile data usage to discern parasitic diseases by identifying hotspots and helping implement eradication efforts (Tao et al., 2023). Another example is a precise agricultural approach, which allows optimal farming during plantation and adapts to severe global warming effects by analyzing data from installed sensors (Zhou et al., 2024). Modern businesses use digital platforms such as technological developments and mobile applications to improve product value addition (Xie et al., 2025b).

Despite its significance, further context remains key to articulating a definitive definition of the digital economy. According to OECD, "digitalization" is derived from goods and services influenced by the ICT (information and communication) sector and from the industrial sector (Karlilar et al., 2023). However, it is also linked to economic activities directly linked to ICTs, including online services. Nonetheless, industrial and economic activities that optimize the economic structure are integral components of digitalization and contribute to industrial development. However, despite such assessment, the digital and ICT infrastructure requires further optimization to foster sustainable economic transformation (Preziuso and Odonkor, 2025).

Apart from digitalization, researchers have also attempted to document how globalization influences international environmental collaboration and competition by eliminating trade barriers to guide capital flows. Huo et al. (2022) reviewed shifts within globalization to argue that financial and trade competitions allow globalization to increase socio-economic welfare by strengthening risk control, diversification of production processes, and promoting technological transfer. In conclusion, as a multidimensional concept, globalization reflects transboundary political, social, and economic affairs (Sharif et al., 2024). In recent years, globalization has also been investigated for its environmental impact as global economies aim to counter unprecedented ecological challenges. An accurate assessment of the environmental effects of globalization will shed new light on the validity of empirical and theoretical modelling and help establish policy benchmarks to achieve sustainable economic development.

Overall, the current study aims to document new evidence in analyzing the effect of digitalization on climate change in the top-10 digital economies. Our extensive research investigation allows this study to contribute in the following ways: First, the limited literature on the role of the digital economy in climate change is limited to countries such as the USA, India, and China. However, no previous study has studied how the digital economy influences ecological sustainability within a specific context, i.e., the top-10 digital economies. Second, in light of the recent economic wave, globalization has gained prominence within modern socio-economic transformation, and its inclusion in the empirical dataset allows this study to investigate the generalization of digital and environmental reforms. Third, we use Driscoll-Kraay standard errors, CS-DL, AMG, and CCEMG within the extended econometric investigation to accurately capture definitive empirical findings. Our empirical investigation allows us to provide several policy implications. (1) Developing and developed economies must increase global capacity to further develop and utilize digital infrastructure, which is expected to influence global environmental sustainability and decarbonization efforts. (2) Our econometric evidence also assists policymakers in establishing policy benchmarks and aims to leverage the full extent to which digitalization can help combat climate change. Fourth, we contextualize green energy transition to study how globalization influences digital economic engagements and how to help accelerate globalization and digitalization to overcome negative environmental challenges. Lastly, our investigation helps fill the decarbonization-digitalization nexus from a globalization perspective.

2 Theoretical and literature review

2.1 Climate change and digital economy

Digitalization as an economic and social progress barometer is central to reshaping international competitiveness, industrial adjustments, and technological advancements. As a result, environmental literature has begun to evaluate the role of digitalization and possible environmental implications. Zhang et al. (2024) evaluated digital economic transformation and the subsequent causality with sustainable development scenarios to conclude that ICT and digital developments have a limited impact on GHG emissions reductions in developed economies. Likewise, Zhou et al. (2019) furthered the digitalization-environment debate by reporting that digital infrastructure degrades environmental quality by depending on carbon-intensive materials to emit GHG and carbon emissions. These arguments allowed Xie et al. (2025b) to investigate digitalization, energy, and resources trends to indicate that ICT and digital infrastructure protect the environment by stipulating that further policy coordination is required so that digital do not outweigh the potential benefits.

A section of studies argued that the digital economy, due to its complex nature, simply cannot be represented by ICT alone, and more theoretical analysis is required to evaluate its scope. Among these, Wu et al. (2023) formed a digital economy index to report that digital transformation remains central to SDG compliance in China at the prefecture level. Additionally, recent studies have used mechanism analysis to suggest that industrial clustering allows the digital economy to gradually preserve ecological sustainability. Xu et al. (2024) used monitored digital and industrialization transition to conclude that the digital economy ensures sustainable industrial transformation and helps monitor resource efficiency. Whereas Cheng and Jin (2022) assessed energy transition to indicate that digitalization promotes energy efficiency, while Peng et al. (2023) reported a non-linear nexus between GHG emissions and digitalization in emerging economies to articulate that structural policy initiatives are key in digital-economic-environment transformation.

Theoretically, the digitalization-climate change association can be illustrated in three ways. First, the digital industry uses modern technological infrastructure to improve environmental sustainability. In general, the internet and technological sector, as a representative of the digital industry, are greener than the conventional industrial sector. Second, products and services from the digital sector help adopt digital technology to increase climate change awareness, provide an accurate environmental assessment, evaluate the effectiveness of market-based environmental regulations, and use information transparency to increase the scope of institutional reforms. Third, the digital industry can help increase industrial value addition, lower industrial emissions, and increase energy efficiency. Yet, digitalization is also attributed to the “rebound effect”, as the digital economy (DE) can offset its impact on carbon reduction (Guo and Kuang, 2025). Bashir et al. (2024) suggested that digitalization requires extensive ICT developments; however, such rapid internet and technological infrastructure developments exacerbate energy demands and degrade environmental quality.

2.2 Climate change and globalization

Globalization as a macroeconomic reform requires coordinated integration of economic, political, and social aspects and has profoundly transformed multinational corporations, financial inclusion, and trade liberalization (Sadiq et al., 2022). Recent research has attempted to shed light on this context by analyzing the environmental impact of globalization, which can be summarized into technical, composition, and scale effects. First, the scale effect from globalization illustrates how trade openness impacts industrial production; hence, several researchers have also used the degree of trade openness as a globalization proxy (Akusta, 2024). This also means that globalization stimulates industrial transformation through excessive resource and energy consumption to exacerbate ecological challenges. Second, the composite effect of globalization allows the technological transfer of low-carbon and green technologies to overcome climate change (Jannat et al., 2025).

The association between globalization and climate change, despite significant academic and policy research, remains controversial. Ibrahim et al. (2024) analyzed sustainable development challenges from globalization by documenting industrial and economic integration in European economies to suggest that globalization hinders environmental and SDG transition. However, Mbe-Nyire Mpuure et al. (2024) investigated the carbon emissions, financial development, and globalization nexus to suggest that technological transfer from globalization improves environmental sustainability. On the contrary, Khan et al. (2019) disputed these outcomes to report that economic, social, and political aspects of globalization push policymakers to pursue industrial transformation and exacerbate environmental conservation. Audi and Ali (2018) evaluated carbon emissions, energy consumption, and globalization in emerging economies to report that globalization requires coherent institutional reforms to overcome ecological challenges. Ali et al. (2025) examined the globalization-energy nexus within the SDG parameters to conclude that industrial transformation in South Asian economies must meet certain economic threshold levels to lower carbon emissions. Similar environmental arguments were reported by Yurtkuran (2021) and Jahanger (2022), who emphasized aligning globalization goals with domestic industrial and environmental policy benchmarks. In light of these arguments, the current study determines that globalization is an essential element within the climate change and environmental quality nexus. However, its association with carbon and GHG emissions is mainly influenced by economic and industrial conditions.

2.3 Collaborative analysis of climate change, globalization, and digital economy

The evaluation of recent globalization and trade activities indicates that it is redefined and facilitated by data flows that embody knowledge, innovation, and information. In addition, digital economic developments have reshaped economic ties that bind industrial and Global South economies, as recent estimates indicate that about 50% of global trade and services have already been digitalized (World Bank, 2024). Such rapid digitalization and economic transformation from globalization have increased cross-border economic cooperation by benefiting from lower communication and transaction costs (Sadiq et al., 2022). Recent research also articulates that further policy refinements in digitalization will increase market efficiency to facilitate global trade and reshape the transfer of goods and services. This also means that digital developments due to globalization are key to users know alternative products and price choices, as information transparency has helped eliminate information asymmetries within market functions. However, such a transition also necessitates digital and conventional communication equipment, which requires energy and resource consumption, which can negatively impact environmental quality.

3 Theoretical background and econometric strategy

3.1 Theoretical background

The current study aims to analyze how the digital economy, economic growth, globalization, industrialization, and urbanization impact climate change in the top-10 digital economies (Denmark, USA, Sweden, Singapore, Switzerland, Netherlands, Finland, South Korea, Canada, Norway). Within the context of modern ecological and sustainability challenges, developments in the digital economy utilize available technological developments to help ecological transformation. According to Goldfarb and Tucker (2019), the digital economy supplements economic activities through spillover and shock effects to lower various business and operational costs. The continuous trend in digitization is essential to SDG evolution as it can facilitate RE transition to improve energy

TABLE 1 Data indicators construction and source details.

Data variables	Data variable	Variable components	Variable proxy	Data source
Digital economy	Digital intelligence	Final subscriptions for fixed telephone	Per 100 people	WDI
		Final subscriptions for fixed broadband	Per 100 people	WDI
		Final subscriptions for cellular use	Per 100 people	WDI
		Telecommunication infrastructure index	—	UN database
	Social implication	Online service index	—	UN database
		Individual internet users	% Of population)	UN database
		E-participation index	—	UN database
	Social solidarity	Service industry value addition (*per capita*)	% (of value addition)	WDI
	Digital trade	ICT exports	% (net exports)	WDI
		ICT imports	% (net imports)	WDI
		Value addition for high and medium-tech value addition	$US per person	WDI
Climate change	Carbon emissions	Net CO_2 emissions	Per metric tons	WDI
	Carbon intensity	CO_2 emissions per dollar of GDP	Carbon efficiency against economic output	Our world in data
	Carbon footprint	Human demand on nature through an ecological accounting system	Net environmental impact	Global footprint network
Gross domestic product	GDP	Goods and services produced per annum	US$ constant 2017	WDI
Globalization	GLOB	Economic and industrial alignment through financial, investment, and trade flows	KOF index value	KOF Swiss economic institute
Industrialization	IND	Industrial value addition	% Share of IVA	WDI
Urbanization	URB	Urban population	% Share within net population	WDI

efficiency and emission reduction effects. As modern economic policies shift towards data analytics, using data elements allows digital economic infrastructure to steadily resolve climate change, as digital information and resource developments positively correlate with value transfer within the industrial sector. These developments also allow industrial value chains to align SDGs with value circulation, where digital infrastructure can be used to ensure environmental sustainability, overall factor productivity, economies of scale, resource efficiency, and increased value circulation throughout economic sectors.

3.2 Main econometric model and variables construction

The current research unpacks the econometric linkage between climate change, digital economy, economic developments, globalization, industrialization, and urbanization from 1995 to 2021. Our basic statistical model for the main investigation can be summarized as Equation 1:

$$CC = f\ (DE, GDP, Glob, IND, URB) \quad (1)$$

where CC is climate change, GDP is economic development, Glob is globalization, IND is industrial value addition, and URB reports urban population in a geographical region. In order to perform an econometric investigation, the current study draws on an annual time-series dataset from various sources. First, in contrast to contemporary literature, the current research has composed a comprehensive digital economy (Table 1) index to accurately measure digital developments by considering information related to digital trade, social solidarity, social implication, and digital intelligence. The value for GDP is taken as GDP *per capita* (US$ constant 2017), industrialization is the share of industrial value addition, and urbanization articulates the share of the urban population within the net population reported each calendar year. The data for globalization considers the globalization score from the KOF index for each economic region. Lastly, we construct a novel climate change index, which consists of data related to net CO_2 emissions, carbon footprint from industrial and manufacturing activities, and carbon intensity to account for ecological performance. It is our opinion that these composite indices are key to predicting and determining economic and environmental progress towards sustainable development goals.

$$DE_{it} = \beta_{0it} + \beta_{1it} DI_{it} + \beta_{2it} SI_{it} + \beta_{3it} SS_{it} + \beta_{4it} DT_{it} + \varepsilon_{it} \quad (2)$$

$$CC_{it} = \beta_{0it} + \beta_{1it}CO_{2it} + \beta_{2it}Carbon\ Intensity_{it} + \beta_3 Carbon\ footprint_{it} + \varepsilon_{it} \quad (3)$$

Based on our consideration of the above-mentioned composite Indices (Equations 2, 3), we derive a testable econometric model as:

$$ln\,CC_{it} = \beta_1\, ln\,DE_{it} + \beta_2 lnGDP_{it} + \beta_3\, ln\,Glob_{it} + \beta_4\, ln\,IND_{it} + \beta_5 URB_{it} + \varepsilon_{it} \quad (4)$$

In addition to the main econometric analysis, we also empirically investigate the EKC hypothesis, which transforms Equation 4 into Equation 5 as:

$$ln\,CC_{it} = \beta_1\, ln\,DE_{it} + \beta_2 lnGDP_{it} + \beta_3 lnGDP\,Square_{it} + \beta_4\, ln\,Glob_{it} + \beta_5\, ln\,IND_{it} + \beta_6 URB_{it} + \varepsilon_{it} \quad (5)$$

Lastly, we also research the interaction term between *DE* and Glob, which helps conceive the final testable econometric Equation 6 as:

$$ln\,CC_{it} = \beta_1\, ln\,DE_{it} + \beta_2 lnGDP_{it} + \beta_3 lnGDP\,Square_{it} + \beta_4\, ln\,Glob_{it} + \beta_5\, ln\,IND_{it} + \beta_6 URB_{it} + \beta_7 DE^{*}Glob_{it} + \varepsilon_{it} \quad (6)$$

3.3 Justification for sample selection and composite index construction through Principal Component Analysis

The current study attempts to analyze how developments within the digital economy, globalization, and climate interact with sustainable development policies in the top-10 leading digital economies of Denmark, the USA, Sweden, Singapore, Switzerland, the Netherlands, Finland, South Korea, Canada, and Norway. The selection of the sampled economies is justified due to the global digital competitiveness ranking based on the World Economic Forum's Networked Readiness Index (NRI) to comprehensively evaluate how modern digital policies aim to leverage communications and information technology to ga ain competitiveness edge. The empirical dataset from the sampled economies has been consistently ranked as top-10 digital economies and has been extensively documented for such performance across technological adoption, e-commerce, and digital business environment, skills, and digital infrastructure. Moreover, recent policy reforms to integrate digital and economic reform to achieve sustainable development transition has enables these countries to become global leaders in digitalization, influenced by strong digital skills, robust ICT sectors, advanced e-government services, and internet penetration.

The current study follows the contemporary research practices where we use Stata software's Principal Component Analysis (PCA) command to construct novel composite indexes of the digital economy and climate change. From a methodological perspective, PCA uses principal components to transform variable components into linear combinations that can capture data variance, which relies on the covariance structure to derive weights rather than being assigned subjectively. To ensure reliable data outcomes, this study standardized all data variables to a zero mean and unit variance before data analysis to ensure comparability across different measurement scales. From a methodological perspective, the PCA command in Stata was performed to extract principal components based on a correlation matrix, where we followed the Kaiser criterion to retain components with eigenvalues greater than one. For each composite index, we retained the first values for principal components to capture maximum covariance related to constituent variables. The index scores were articulated using the predict command in the Stata software to ascertain the score option. As mentioned in the Stata technical resources, these scores illustrate first principal components' eigenvector loadings represent a standardized variable's linear combination. The use of this approach, variables showing greater influence over the primary construct receive higher weights to determine final index values.

3.4 Preliminary econometric tests

The inclusion of a robust and comprehensive econometric strategy is key to providing definite econometric evidence and solve research gap within available literature (Chen et al., 2025; Wu et al., 2024). The current study divides econometric strategy into two distinct sections, where initially we test various econometric assessments under the scope of preliminary and long-run tests. This study proceeds with a preliminary econometric strategy by testing the cross-sectional dependency within the sampled dataset. This allowed the researchers to evaluate the influence of cross-border and inter-regional economic cooperation on data indicators and how it can impact the statistical authenticity. Within this regard, the current study also relies on several CSD tests to help us evaluate CSD influence within the dataset, as this approach is key to identifying and reporting statistical inconsistencies. Furthermore, CSD analysis is accompanied by Pesaran and Yamagata tests to determine slope heterogeneity through beta and its adjacent for the sampled economies.

In order to report shocks from undetected errors from CSD, initial econometric analysis also uses unit root analysis, where we have chosen CIPS and CADF to report data stationary properties. The primary reason for using these tests over the prior generation of unit root analysis is that these tests can tackle data cross-sectional issues during the analytical process to provide consistent empirical inferences. The last step of the preliminary econometric test requires us to use Westerlund cointegration properties, which help determine long-run association across data indicators. The primary analytical process within Westerlund cointegration tests involves using a bootstrap statistical approach for group and panel statistics to report empirical distortions through asymptotic distribution.

3.5 Long-run econometric strategy

For the main econometric investigation, the current study has used Driscoll and Kraay standard error, CS-DL, AMG, and CCEMG. First, we adopt Driscoll and Kraay to study the empirical association from climate change, green energy investments, energy transition, trade openness, and banking developments towards energy security risks. The current research prefers Driscoll and Kraay standard error over other empirical approaches as it is more efficient in tackling

TABLE 2 Descriptive statistics.

Data statistics	CC	DE	GDP	Glob	IND	URB
Mean	7.902666	2.775771	11.85826	1.917756	1.173450	7.078532
Median	7.542757	2.766822	11.69400	1.922411	1.164697	6.839066
Maximum	9.488018	3.185897	13.32488	1.958704	1.450815	8.439592
Minimum	7.312842	2.304404	11.20654	1.755978	0.749112	6.507385
Std. Dev	0.648595	0.158216	0.536762	0.032487	0.157182	0.549881
Skewness	0.464417	−1.21540435	−0.04380192	0.35842835	−0.74695365	−0.576308
Kurtosis	2.2481142	3.4710169	2.41328064	2.40935675	4.31071335	1.77844655
Jarque-bera	8.86512735	45.5522245	1.61491776	5.12404255	31.5920125	17.9238685
Probability	0.14194045	0.31477965	0.4139856	0.25404615	0.3509471	0.270826
Observations	270	270	270	270	270	270

econometric issues of heteroscedasticity, auto-correlation and CSD. Additionally, it controls missing values, eliminates covariance matrix approximations, and is useful for balanced or unbalanced datasets. Driscoll and Kraay standard error determines residuals and then subsequently calculates the estimator of “weighted heteroscedasticity and autocorrelation consistent.”

We also used AMG, CCEMG, and CS-DL to evaluate the authenticity of the statistical analysis further. The empirical tests of the Augmented Mean Group estimator and the Common Correlated Effects Mean Group. Lies in the ability of these approaches to solve statistical issues related to non-stationary, cointegration breakdowns, heterogeneity, and CSD. In addition, these approaches are also suitable for moderately sized statistical panels. The primary econometric approach for these aforementioned tests utilizes averages from cross-sections to tests analytical association between dependent and independent data indicators under consideration. In addition to AMG and CCEMG, we also consider CS-DL as an additional robustness check, as this approach solves data cross-sectional and multi-collinearity issues by accounting for average CSD, and during econometric investigation, it can drop them if necessary. The current study also uses Dumitrescu–Hurlin Granger causality test to document the degree to which data causality exists within empirical variables. The DH approach is suitable as it allows coefficient parameters to be flexible and solves CSD to provide robust empirical statistics. Lastly, the DH test is applicable in case the empirical model is heterogeneous and unbalanced.

4 Empirical findings and discussion

The current section provides details about empirical findings from preliminary and long-run econometric analysis. Such a robust and extensive analytical approach is key to ensuring statistical accuracy, and the reported empirical association is key to providing relevant policy suggestions aimed at improving sustainable development compliance and environmental sustainability. Within this context, we begin with reporting basic data properties (Tables 2, 3) to provide details about descriptive statistics and the correlation matrix. First, we report that the mean values for CC, DE, GDP, Glob, IND, and URB are 7.902, 2.775, 11.858, 1.917, 1.1734, and 7.078, whereas the median values for variables under consideration are 7.542, 2.7668, 11.694, 1.922, 1.164, and 6.839, respectively. In addition, standard deviation estimates are reported as 0.648, 0.158, 0.536, 0.0324, 0.157, and 0.549. In addition, our observations in relation to skewness, kurtosis, and Jarque-bera are of the indication that the descriptive statistics meet the general acceptable statistical standards.

TABLE 3 Correlation matrix.

Data variables	CC	DE	GDP	GLOB	IND	URB
CC	1.000000					
DE	−0.323271	1.000000				
GDP	0.963865	−0.137809	1.000000			
Glob	−0.435869	0.482378	−0.299310	1.000000		
IND	−0.022841	0.234033	−0.079221	−0.449440	1.000000	
URB	0.986451	−0.255944	0.978597	−0.422566	0.010003	1.000000

In the current section, we report and discuss the main empirical findings and discuss environmental policy modifications. As per the empirical strategy section, we discuss cross-sectional dependency and slope heterogeneity, followed by stationary properties and cointegration tests. First, Table 4 provides statistical information to outline whether CSD exists to identify if regional or global macroeconomic shocks influence the data variables under consideration. As per empirical findings (Table 3), all variables included in the empirical strategy are highly significant, indicating the strong possibility of cross-sectional dependency within the dataset. In addition, delta and adjusted are highly significant to indicate current empirical model suffers from slope heterogeneity.

The confirmation of cross-sectional dependency and slope heterogeneity provides us opportunity to determine if data are stationary at the level or first difference through second-generation tests, which show greater statistical reliability than

TABLE 4 **Cross-sectional dependence and slope heterogeneity tests.**

Tests	CC	DE	GDP	GLOB	IND	URB
Breusch-pagan LM	440.6925	752.0628	1156.047	1085.544	648.6531	1154.516
Pesaran scaled LM	41.70965	74.53096	117.1146	109.6829	63.63062	116.9532
Bias-corrected scaled LM	41.51734	74.33865	116.9223	109.4906	63.43832	116.7609
Pesaran CD	6.652169	26.91817	33.99246	32.92861	17.42130	33.96741

Slope heterogeneity tests		
	Coeff	P value
Delta	11.741	0.000
adj	13.997	0.000

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

TABLE 5 **CIPS and CADF unit root tests.**

Variables	CIPS		CADF	
	Level	Difference	Level	Difference
CC	−2.137	−5.822*	−1.690	−4.965*
DE	−1.668	−4.591*	−1.561	−3.811*
GDP	−2.135	−3.946*	−2.391**	-
Glob	−3.105*	-	−2.415**	-
IND	−1.726	−4.205*	−2.008	−3.368*
URB	−2.460**	-	−3.166**	-

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

TABLE 6 **Westerlund Cointegration test.**

Statistic	Value	Z value	Robust P-value
Gt	−3.991***	3.801	0.00
Ga	−9.199***	2.797	0.00
Pt	−11.503***	3.117	0.00
Pa	−13.596***	0.098	0.00

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

first-generation tests. As per empirical findings reported in Table 5, we confirm mix order of unit root as the CIPS test confirms that Glob and URB at the level, whereas CC, DE, GDP, and IND show statistical significance at the difference. Second, GDP, Glob, and URB are significant at the level, whereas CC, DE, and IND have statistical significance at a difference.

Our analysis of CSD and stationary properties allows us to proceed with the Westerlund cointegration test as an econometric approach to confirm if variables under econometric consideration share cointegration. As per empirical estimates in Table 6, all indicators of G_t, G_a, P_t, and P_a are highly significant to confirm the existence of data cointegration.

TABLE 7 **Driscoll-Kraay standard errors.**

Variables	Model 1		Model 2	
	Coefficient	p value	Coefficient	p value
DE	−0.526**	0.032	−0.791*	0.089
GDP	1.410**	0.015	0.965**	0.031
GDP^2	−0.074**	0.002	−0.051**	0.026
Glob	0.434**	0.050	0.679**	0.048
IND	0.249**	0.042	0.237**	0.016
URB	0.754*	0.070	0.858**	0.022
DE*Glob	-	-	−0.891**	0.019

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

Finally, we report the discussion of empirical findings of Driscoll-Kraay standard errors related to climate change, economic development, globalization, industrialization, and urban population in top-digital economies. First, our findings from Table 7 indicate that the digital economy shares a negative association with climate change in the long run. Such an econometric outcome allows the current study to articulate that digital economic developments are key to industrial transformation and technological optimization to reorganize economic and energy structures, which is essential to green energy transition and environmental sustainability (Qian et al., 2025; Xiaobin et al., 2024). The available evidence also suggests that digital developments promote inter-regional collaboration and optimized energy ecology to ensure consistent SDG progress. Furthermore, intelligence and informatization through the digital economy in the industrial supply chain (Xiang et al., 2022) promote technological innovation, including solar and photovoltaic power to offset the carbon footprint from traditional energy consumption (Li et al., 2025). Lastly, digital economic developments positively correlate with the operation of energy systems to lower energy costs and enhance energy supply to eradicate energy poverty as well.

TABLE 8 CS-DL, AMG & CCEMG.

Data variables	CS-DL		AMG		CCEMG	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
DE	−0.383**	−0.498*	−0.168**	−0.237**	−0.377**	−0.525**
GDP	1.189*	1.064**	2.986*	1.014***	1.297**	1.646**
GDP^2	−0.469**	−0.684**	−0.693**	−0.759*	−0.623**	−0.467**
Glob	0.624**	0.555*	0.542**	0.693***	0.415**	0.805*
IND	0.119**	0.602**	0.184**	0.172**	0.127***	0.408*
URB	1.685**	0.806**	0.465**	0.201**	0.877*	0.844**
DE*Glob		−0.718**		−0.635**		−0.849**

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

Next, we validate the inverted EKC hypothesis for GDP and climate change, where the association from GDP is an indication that industrial and economic transformation initially deteriorates environmental sustainability, but GHG and environmental variables gradually decline as industrial expansion progresses past the tipping point of GDP (Feng et al., 2024). Such empirical association supports the inverted U-shape association between economic developments and climate change that has been previously hypothesized as well. In addition, several researchers (Bacchetta et al., 2025; Liu et al., 2024; Ma et al., 2023b) have argued that economic practices in developed economies tend to carry a negative long-term association with environmental degradation, which implies that these economies invest revenue from financial growth in industrial and economic areas where they can decrease pollution output. Our findings align with recent empirical environmental studies (Jannat et al., 2025; Requena-i-Mora et al., 2025) where scholars have proposed policy reforms to align environmental and economic coordination to limit ecological degradation (Ma et al., 2023a).

Next, the empirical association between globalization and industrial value addition towards climate change is positive and significant. These standpoints are similar to Gaies and Jahmane (2022), Ali et al. (2025), Akusta (2024), and Wang et al. (2020), who pointed out that globalization and the industrial sector exacerbate ecological challenges. Theoretically, economic liberalization and the subsequent industrial developments take advantage of financial and trade policies (Xie et al., 2025a), but subsequent trade openness effects generally degrade the environment. This is because policymakers are preoccupied with integrating technological, financial, and economic constraints to avoid vulnerabilities linked with consumption, production, and energy availability for the industrial sector (Sharif et al., 2024). In addition, as digital economic platforms increasingly become globalized, entrepreneurs and small businesses' participation in economic activities puts pressure on environmental progress. To tackle stringent environmental policies, multinational firms often shift production plants to developing economies to take advantage of trade globalization and lax regulatory approaches, although it exacerbates environmental pressure (Bashir et al., 2025a; Naveed et al., 2025).

Lastly, the empirical association between urbanization and climate change is positive in both econometric models. Such empirical outcomes are justifiable as sampled economies under consideration have greater urban levels; as a result, such urban density disproportionately impacts demand for energy resources, leading to environmental degradation (Chien, 2024). In addition, the post-pandemic economic rebound has increased economic opportunities, which have led to higher expenditures on food, transportation, accommodation, and public utilities. Shi et al. (2025) pointed out that finite resource availability leads to an unsustainable push for natural resources, which further degrades ecological sustainability. A similar econometric association has been reported by Artekin and Kalayci (2025), Tan et al. (2023), and Bashir et al. (2022).

In extension to Driscoll-Kraay standard errors, the current study further reports econometric findings from CS-DL, AMG and CCEMG to check the authenticity of the main empirical analysis. As per findings reported in Table 8, the values for DE remain negative, while Glob, IND, and URB are positive. In addition, we further confirm the inverted EKC hypothesis related to economic transformation and how it affects climate change in the top-10 digital economies. Lastly, the interaction between DE*Glob remains negative, which further provides evidence that digitalization in top-10 digital economies is a critical factor in environmental sustainability. Our empirical findings allow us to report that the digital economy integrates IoT and smart grid enables systems to optimize GHG emissions and energy efficiency, which allows digital platforms to cut down industrial pollution and transportation (Bashir et al., 2025b). Furthermore, the integration of digital and economic policies allows policymakers to use blockchain infrastructure in enhancing transparency in green finance, sustainable supply chains, and carbon tracking to foster consumption and production patterns. This study also reports positive associations from globalization, industrialization, and urbanization, where globalization generally degrades environmental sustainability due to higher cross-border trade and transportation; industrialization drives fossil fuel consumption and energy-intensive manufacturing activities, while urbanization harms environmental sustainability by impacting urban waste generation, higher energy consumption, and land use changes in densely populated urban areas. Lastly, we also

TABLE 9 Pairwise dumitrescu-hurlin panel causality tests.

Data variables	CC	DE	GDP	Glob	IND	URB
CC	-	2.864	4.156**	1.471	2.496	4.122**
DE	7.490	-	2.260	2.439	6.874	5.605
GDP	4.715**	6.409	-	3.277	7.692	10.150***
Glob	4.663**	3.854**	2.512	-	5.205**	8.985***
IND	5.258**	1.659	2.708	5.471	-	3.026
URB	7.616	7.559	4.932**	4.969**	7.690	-

***, ** and * indicates significance level at 1%, 5%, and 10%, respectively.

validate the inverted U-shaped EKC hypothesis for GDP, which allows us to report that during preliminary industrial and economic processes, environmental quality improves, but the eventual integration of energy and environmental infrastructure tends to resolve climate change threats (Rasheed et al., 2026). However, recent research has emphasized that strict environmental policies are essential to the validity of inverted EKC and how economic growth can help reverse environmental damage, especially if consumption-oriented lifestyles persist in wealthy nations. Our extended econometric and robustness analysis helps us report extended policy suggestions to improve the role of digital and macroeconomic factors in climate change challenges.

Lastly, we use the Dumitrescu-Hurlin causality test (Table 9) to determine Granger causality within empirical datasets, which is widely used within contemporary research as it accounts for heterogeneity and CSD to provide statistically robust findings compared to contemporary causality analyses. Additionally, DH causality analysis allows for varied causal associations across different units, making it suitable for econometric investigations using datasets from diverse regions or economies. Our empirical findings for the current study allow us to report that CC shares dual causality with GDP and unidirectional causality with URB, meaning any shift in CC has a reciprocal shift in GDP, while any shift in CC influences URB, but URB does not Granger cause in return. On the other hand, GDP and Glob have a bidirectional association with URB, where any movement within globalization and economic growth influences URB, and likewise any shift in URB brings a corresponding change in return. However, Glob also unilaterally gangers cause CC, DE, and IND, which allows us to report that any statistical variation in Glob causes a significant change in climate change, digital economy, and industrialization, but any shift in CC, DE, and IND has no econometric impact on Glob in the long run. Lastly, IND shares unilateral Granger casualty with CC in the top digital economies in the long run, which is indicative that empirical variation in IND influences climate change, but no corresponding shift is observed from climate change towards IND.

5 Conclusion and policy suggestions

Amidst rapid economic transformation, environmental sustainability has emerged as a key policy issue. In order to extend policy debate, the current study explores the digital economy–climate change-globalization nexus in the top-10 digital economies. This research relies on Driscoll-Kraay standard errors, CS-DL, AMG, and CCEMG as primary econometric strategies to extend energy economic literature by incorporating novel climate change and digital economy indices. We provide empirical evidence by confirming CSD, slope heterogeneity, unit root, and long-term cointegration association within the panel dataset. This study also performs an extended econometric analysis to infer that the digital economy and globalization help lower climate change threats, while urbanization and industrialization contribute to environmental challenges. We also confirm the inverted EKC hypothesis, meaning sampled economies must achieve certain threshold levels to lower climate externalities. Lastly, this study utilizes the DH causality test to confirm unilateral and bidirectional causal associations within data variables.

Our econometric analysis allows us to report novel policy implications. First, policymakers must strengthen digital infrastructure to facilitate spillover effects from the digital economy and allow policymakers to circumvent the “polarization effect”. Second, regional-level sharing protocols must be established to share digital resources without geopolitical or associated barriers; this will enable policymakers to test business models and intelligent economies with unique features as per the SDG agenda. Third, in order to resolve challenges associated with insufficient digital and information infrastructure, further policy reforms to encourage the construction of critical information infrastructure will allow policymakers to overcome the risks associated with the “digital divide” in digital economies. Fourth, the current research proposes the cultivation of composite talents related to policy management and digital technologies that will supplement digital economic developments and help avoid inverted “U” inflection points of sustainable development compliance. Lastly, we further propose consolidating environmental protection technologies and digital infrastructure benchmarks, and continuously optimizing policy evaluation criteria to address energy and operational costs of the digital economic transition.

In order to further foster sustainable development progress, the current study further proposes novel policy benchmarks aimed at strategic rethinking of globalization and economic growth metrics. First, the environmental protective role of globalization requires active policy collaboration to offset the adverse effects associated with industrialization and globalization. The primary consideration of such initiatives requires time-specified sustainable development goals to overcome contemporary climate change challenges. Second, due to globalization’s wider impact on the economics, employment, and transport sectors, inadequate policy coordination can hinder environmental progress through traditional technologies. In this context, the current research suggests that globalization and key climate change and environmental tool to improve environmental outcomes. Third, policymakers can gradually impose carbon, pollution, and resource depletion pricing mechanisms to improve SDG performance from globalization activities. Fourth, from economic and industrial aspects, global policy shifts to promote domestic supply chain procurement, safeguard the environmental performance of logistics, and encourage industrial sectors to limit supply chain emission risks. Lastly, a stringent sustainability regulatory approach remains key to stimulating inter-regional environmentally protective economic activities. However, the trade of products and services can increase energy and resource consumption; hence, environmental protective campaigns must be promoted to increase general public awareness, especially related to the production of digital goods and services.

Lastly, despite novel empirical evidence, the current study has also identified some research limitations that future studies can address. First, further research focused at digital economy-environment nexus within the context of geographical contexts, including the Global South, service-focused countries, and digital export economies, can offer further policy insights. Second, within the context of digital infrastructure developments, dynamic modelling investigations to evaluate how institutional policy shifts influence the digitalization process can offer comparative SDG evidence across developed and developing economies. Third, researchers can attempt to identify how digital economic expansion within the contemporary regulatory structures can identify key issues within environmental and ecological issues.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

MFB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. AQ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review and editing. MB: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing. ZM: Conceptualization, Data curation, Methodology, Resources, Supervision, Writing – original draft, Writing – review and editing.

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Conflict of interest

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