Received: 27 January 2026 | Revised: 25 August 2026 | Accepted: 03 September 2026

https://doi.org/10.56946/jeee.v5i2.931
Volume 5 (2): 1-12

Journal of Environmental and Energy Economics

Research Article

The Impact of the Digital Economy on CO_2 Emissions: Evidence from BRI Countries

Iqra[1], Khadija Ashfaq[2], Fahim Khan[3*]
[1]Department of Economics, Allama Iqbal Open University, Islamabad, Pakistan.
[2]Fatima Jinnah Women University Rawalpindi, Pakistan.
[3]National University of Technology (NUTECH). Karnal Sher Khan Shaheed (IJP Road), Sector I-12, Islamabad .Pakistan.

[*]Correspondence author: Fahim Khan (fahimkhan.nusash@nutech.edu.pk)

Abstract

This study investigates the impact of the digital economy on CO_2 emissions using a panel dataset of 140 Belt and Road Initiative (BRI) countries over the period 2001–2023. The analysis employs a comprehensive panel data framework to examine both the direct and nonlinear effects of digital development on environmental degradation. The digital economy is measured using both a composite index and individual indicators, including internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and secure internet servers. The empirical results show that the digital economy has a significant and nonlinear relationship with CO_2 emissions. At early stages of development, digitalization tends to increase emissions due to higher energy consumption associated with ICT infrastructure expansion. However, at more advanced stages, digital development contributes to emissions reduction, indicating the presence of a "digital Kuznets curve" effect. Among control variables, GDP, population, and energy consumption consistently increase CO_2 emissions, while trade openness shows a mitigating effect in some specifications. Foreign direct investment is found to exert a positive impact on emissions in dynamic models, suggesting a pollution-intensive composition of capital inflows in BRI economies. Overall, the findings highlight that the environmental impact of the digital economy is heterogeneous and depends on the level of digital development. The results suggest that policy efforts should focus on promoting energy-efficient digital infrastructure and supporting green digital transformation to ensure that digitalization contributes to sustainable environmental outcomes.

Keywords: Digital economy, CO_2 emissions, Panel Data, System GMM, Environmental Kuznets Curve, ICT, Renewable Energy, Economic Growth, Sustainability.

1. Introduction

Climate change remains one of the most pressing global challenges of the twenty-first century, primarily driven by the continuous increase in greenhouse gas emissions, particularly carbon dioxide (CO_2). Despite international efforts such as the Paris Agreement and various national decarbonization strategies, global CO_2 emissions continue to rise due to economic growth, population expansion, and increasing energy demand [1, 2]. Consequently, identifying sustainable pathways that reconcile economic development with environmental protection has become a central objective for policymakers and researchers worldwide.

In recent years, the rapid expansion of the digital economy has emerged as a transformative force reshaping production systems, consumption patterns, communication networks, and business operations. The digital economy encompasses a broad range of technologies and activities, including internet connectivity, broadband infrastructure, mobile communications, cloud computing, artificial intelligence (AI), and digital services. These technologies have significantly enhanced productivity, innovation, and economic efficiency, thereby contributing to economic growth and social development [3].

However, the environmental implications of digitalization remain controversial. On the one hand, digital technologies can facilitate energy efficiency, optimize resource allocation, promote smart manufacturing, support remote working, and reduce transaction costs, all of which may contribute to lower carbon emissions [4, 5]. On the other hand, the expansion of digital infrastructure—including data centers, communication networks, and cloud-computing facilities—requires substantial electricity consumption, potentially increasing carbon emissions, particularly in countries that rely heavily on fossil-fuel-based energy

systems [6, 7]. The rapid growth of AI applications and data-intensive technologies has further intensified concerns regarding the environmental footprint of the digital sector.

Existing empirical evidence on the relationship between the digital economy and environmental quality remains inconclusive. Some studies report that digitalization contributes to emission reductions through technological innovation, improved efficiency, and structural transformation toward less carbon-intensive economic activities [3, 8]. Conversely, other studies suggest that digital development may initially increase emissions because of higher energy consumption associated with information and communication technology (ICT) infrastructure and digital services [6, 9]. These contrasting findings imply that the environmental impact of digitalization may not be linear but may vary across different stages of digital development.

This argument is closely related to the emerging concept of the Digital Environmental Kuznets Curve (DEKC), which proposes that digitalization initially increases environmental pressure but eventually contributes to environmental improvement once digital technologies reach a sufficiently advanced stage [9, 10]. Under this framework, the scale effects associated with expanding digital infrastructure may dominate during the early stages of development, whereas efficiency gains, technological innovation, and smart resource management become more important as digital maturity increases.

Although the literature on digitalization and environmental sustainability has grown rapidly, several important gaps remain. First, many studies focus on individual countries or specific regions, limiting the generalizability of their findings. Second, existing research often relies on a single proxy for digitalization, which may not adequately capture the multidimensional nature of the digital economy. Third, evidence from Belt and Road Initiative (BRI) countries remains relatively limited despite their growing importance in global economic activity, digital transformation, and carbon emissions.

To address these gaps, this study investigates the impact of the digital economy on CO_2 emissions using a panel dataset covering 140 BRI countries from 2001 to 2023. Unlike previous studies, the analysis employs both a composite digital economy index and several individual digital indicators, including internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and secure internet servers. Furthermore, the study examines potential nonlinear effects of digitalization on environmental quality by testing the Digital Environmental Kuznets Curve hypothesis using advanced panel-data estimation techniques.

This study contributes to the literature in three important ways. First, it provides comprehensive evidence on the environmental consequences of digitalization across a large sample of BRI countries. Second, it evaluates the heterogeneous effects of different dimensions of digital infrastructure on CO_2 emissions. Third, it investigates the existence of a nonlinear relationship between digitalization and environmental degradation, thereby offering new insights into the role of digital transformation in achieving sustainable development goals. The findings provide valuable policy implications for governments seeking to balance digital development with environmental sustainability and climate-change mitigation objectives.

2. Literature Review

The relationship between digitalization and environmental sustainability has attracted increasing scholarly attention over the past decade. As digital technologies continue to transform economic activities, researchers have sought to determine whether the digital economy contributes to environmental degradation or facilitates the transition toward low-carbon development. Existing studies suggest that the environmental effects of digitalization are complex and may operate through multiple channels, including technological innovation, energy efficiency improvements, industrial restructuring, and changes in consumption behavior [11, 12].

A growing body of literature argues that digitalization can contribute positively to environmental quality through efficiency-enhancing mechanisms. Digital technologies improve information flows, reduce transaction costs, optimize production processes, and facilitate the adoption of smart energy-management systems. These improvements can increase resource-use efficiency and reduce energy waste, thereby lowering carbon emissions [13, 14]. Furthermore, digital transformation promotes green innovation by accelerating technological diffusion, enhancing research and development activities, and supporting the deployment of environmentally friendly technologies [15]. Several empirical studies have found that countries with higher levels of digital

development tend to exhibit better environmental performance due to increased technological efficiency and cleaner production processes [16].

However, another strand of literature emphasizes the environmental costs associated with digital expansion. The rapid growth of internet usage, cloud computing, artificial intelligence, blockchain technologies, and data centers has substantially increased electricity demand worldwide. The operation of digital infrastructure requires significant energy inputs, particularly in economies where electricity generation remains dependent on fossil fuels [17, 18]. Consequently, digitalization may initially increase carbon emissions by expanding energy-intensive ICT infrastructure and stimulating greater economic activity. This perspective highlights the existence of a scale effect, whereby the environmental burden associated with digital growth outweighs efficiency gains during the early stages of digital development [19].

Recent empirical studies increasingly suggest that the impact of the digital economy on CO_2 emissions is nonlinear. Drawing on the Environmental Kuznets Curve (EKC) framework, researchers argue that digitalization may initially worsen environmental quality but subsequently contribute to emissions reduction after reaching a certain level of technological maturity [20]. This proposition has been described as the Digital Environmental Kuznets Curve (DEKC), according to which the environmental effects of digitalization evolve over different stages of development. In the early stages, infrastructure expansion, increased electricity consumption, and rising digital-device usage contribute to higher emissions. As digital technologies mature, however, improvements in energy efficiency, smart production systems, and technological innovation become more dominant, resulting in lower emissions [21, 22].

Several recent studies provide empirical support for this nonlinear relationship. Sun et al. [23] reported that digital development initially increases carbon emissions but eventually promotes environmental improvement once digitalization surpasses a critical threshold. Similarly, Sun and Wu [24] found that digital transformation influences emissions through changes in energy structure and technological efficiency, producing heterogeneous environmental effects across different development stages. Evidence from regional and city-level analyses further indicates that advanced digital economies are more capable of reducing emissions through industrial upgrading, innovation, and efficient resource allocation [25, 26].

The environmental consequences of digitalization also vary across different dimensions of digital infrastructure. Internet penetration, broadband connectivity, mobile communication networks, and digital security systems may exert distinct effects on environmental outcomes. Internet access and broadband expansion can support remote working, e-commerce, digital services, and virtual communication, reducing transportation-related emissions and improving resource efficiency [27]. At the same time, the expansion of communication networks and digital devices increases electricity demand and electronic waste generation, potentially offsetting environmental benefits [28]. Consequently, the net environmental effect of digital infrastructure remains an empirical question that depends on the level of technological development and energy-system characteristics.

Another important aspect of the literature concerns the growing carbon footprint of the digital sector itself. Recent estimates indicate that the ICT sector accounts for a rising share of global electricity consumption and greenhouse-gas emissions. The rapid expansion of artificial intelligence, cloud computing, and large-scale data centers has intensified concerns regarding the sustainability of digital growth [29]. Major technology firms have reported substantial increases in electricity consumption associated with AI applications, highlighting the need to balance technological advancement with environmental sustainability objectives [30].

In addition to digitalization, the literature identifies several socioeconomic factors that influence CO_2 emissions. Economic growth remains one of the most widely studied determinants of environmental degradation. According to the traditional EKC framework, economic expansion initially increases emissions through greater production and energy consumption but may eventually improve environmental quality as income levels rise and environmental awareness increases [20, 31]. Population growth is also associated with higher energy demand, resource consumption, and environmental pressure, consistent with the IPAT framework [32]. Similarly, energy consumption, particularly from fossil-fuel sources, is consistently identified as a major driver of carbon emissions across both developed and developing economies [33].

The roles of foreign direct investment (FDI) and trade openness remain more controversial. The pollution haven hypothesis suggests that multinational firms may relocate pollution-intensive activities to countries with relatively weak environmental regulations, thereby increasing emissions [34]. In contrast, the pollution halo hypothesis argues that foreign investment can facilitate technology transfer and improve environmental performance through the adoption of cleaner production methods [35]. Likewise, trade openness may either increase emissions through expanded production and transportation activities or reduce emissions through technology diffusion and efficiency gains [36].

Despite the rapidly expanding literature, several research gaps remain. First, most existing studies focus on individual countries or specific regions, limiting the external validity of their findings. Second, many studies rely on a single indicator of digitalization, which may not fully capture the multidimensional nature of the digital economy. Third, empirical evidence from Belt and Road Initiative (BRI) countries remains relatively scarce despite their increasing importance in global digital transformation and carbon-emission dynamics. Therefore, further investigation using comprehensive measures of the digital economy and robust econometric approaches is needed to better understand the relationship between digitalization and environmental sustainability across a large sample of countries.

3. Methodology

This study employs a balanced panel dataset of 140 Belt and Road Initiative (BRI) countries over the period 2001–2023 to examine the impact of the digital economy on CO_2 emissions. The data are structured in a country-year format, which allows the analysis to capture both cross-country heterogeneity and time-series variation in environmental and digital development indicators.

The panel framework is particularly suitable for this study as it enables the identification of dynamic relationships between digitalization and environmental outcomes while accounting for unobserved country-specific characteristics that may influence CO_2 emissions, such as institutional quality, technological capacity, and structural differences in economic development. This approach provides a robust basis for evaluating how the digital economy affects environmental performance across diverse economies over time.

3.1 Data and Variables

The dependent variable in this study is carbon dioxide (CO_2) emissions, used as a proxy for environmental degradation. The key explanatory variable is the digital economy, which captures the level of digital development in each country. The digital economy is typically proxied using indicators such as internet usage, broadband penetration, mobile subscriptions, digital infrastructure development, or composite digital economy indices.

In addition to the main explanatory variable, the model includes a set of control variables to reduce omitted variable bias and isolate the effect of the digital economy on emissions. These commonly include economic growth (GDP per capita), population size, energy consumption (particularly fossil fuel energy use), trade openness, and foreign direct investment (FDI). These variables are included because they are widely recognized in the literature as important determinants of environmental degradation and may influence CO_2 emissions directly or indirectly.

3.2 Empirical Model Specification

To estimate the relationship between the digital economy and CO_2 emissions, the following baseline econometric model is specified:

$$CO_2_it = \beta_0 + \beta_1 \ DigitalEconomy_it + \beta_2 \ GDP_it + \beta_3 \ POP_it + \beta_4 \ EnergyUse_it + \beta_5 \ FDI_it + \beta_6 \ Trade_it + \varepsilon_it$$

where i represents country and t represents time. The coefficient β_1 captures the effect of the digital economy on CO_2 emissions.

To account for possible non-linearities, an extended specification may include a squared term of the digital economy:

$$CO_2_it = \beta_0 + \beta_1 \ DigitalEconomy_it + \beta_2 \ DigitalEconomy^2_it + \beta_3 \ X_it + \varepsilon_it$$

where X_it represents the vector of control variables. This allows testing whether the environmental impact of digitalization changes at different stages of digital development.

3.4 Econometric Approach

The study employs panel data estimation techniques to address unobserved heterogeneity and improve estimation accuracy. The initial approach uses pooled Ordinary Least Squares (OLS) as a baseline model, which assumes homogeneity across countries. However, since countries differ in institutional quality, technological capacity, and environmental policies, this method may suffer from omitted variable bias.

To address this limitation, the Fixed Effects (FE) model is used, which controls for time-invariant country-specific characteristics by allowing individual intercepts for each country. This approach focuses on within-country variation over time and provides more reliable estimates when unobserved heterogeneity is present.

Given the possibility of endogeneity between digitalization and CO_2 emissions—arising from reverse causality, omitted variables, or dynamic effects—the study further employs System Generalized Method of Moments (System GMM). This estimator is particularly suitable for dynamic panel data models where past emissions may influence current emissions. System GMM combines equations in levels and first differences and uses lagged values of endogenous variables as instruments, improving efficiency and reducing bias in the presence of endogeneity.

4. Results and Discussion

4.1. Descriptive Statistics and Correlation Analysis

Table 1 presents the descriptive statistics of the study variables. The average value of CO_2 emissions is 3.98 metric tons per capita, with substantial variation across countries, indicating significant heterogeneity in environmental performance among BRI economies. The digital economy index (DE) exhibits considerable dispersion, reflecting different stages of digital development across the sample. Similarly, GDP growth, energy consumption, FDI inflows, and trade openness show large variations, suggesting differences in economic structures and development levels among participating countries.

Table 2 reports the pairwise correlation matrix. The digital economy index is positively correlated with CO_2 emissions, providing preliminary evidence that digitalization may contribute to environmental pressure. Energy consumption exhibits the strongest positive correlation with emissions, highlighting its central role in environmental degradation. The correlations among explanatory variables remain below conventional multicollinearity thresholds, indicating that multicollinearity is unlikely to be a serious concern in the empirical analysis.

Table 1. Summary statistics of the variables used in the analysis.

Variable	Mean	Std. Dev.	Min	Max
co2	3.975912	5.662005	0	47.65696
de	-0.0108275	0.990456	-1.004583	3.347466
gdp	3.789292	6.425764	-58.31823	153.4926
pop	53.43795	21.90342	12.978	100
enr	2141.676	2816.426	9.579196	21420.63
fdi	5.410538	20.06842	-440.1307	449.0828
tr	89.31215	53.23824	2.208444	437.3267

Table 2. Pairwise correlation matrix of the study variables.

	co2	de	gdp	pop	enr	fdi	tr
co2	1						
de	0.3895	1					
gdp	0.0247	0.291	1				
pop	0.5811	0.5304	0.1136	1			
enr	0.9741	0.3552	0.0216	0.5687	1		
fdi	0.0325	0.2161	0.0655	0.0824	0.0021	1	
tr	0.328	0.395	0.02	0.3797	0.3257	0.262	1

4.2. Baseline Results: Impact of the Digital Economy on CO_2 Emissions

Table 3 reports the baseline estimation results obtained from pooled OLS, fixed effects (FE), Difference GMM, and System GMM models. Across all specifications, the coefficient of the digital economy index remains positive and statistically significant, suggesting that digital development contributes to higher CO_2 emissions in BRI countries. The positive relationship indicates that the expansion of digital infrastructure, internet connectivity, communication networks, and digital services increases energy demand, thereby raising carbon emissions. The result supports the scale-effect argument, which suggests that digital transformation initially stimulates economic activity and energy consumption faster than efficiency improvements can offset environmental costs. These findings are consistent with previous studies reporting that ICT infrastructure and digital expansion increase electricity consumption and carbon emissions, particularly in developing economies [17, 18].

Table 3. Effect of digital economy on carbon emission.

VARIABLES	(1) co2	(2) co2	(3) co2	(4) co2
de	0.500***	1.119***	1.465***	0.0700***
	(0.129)	(0.193)	(0.00621)	(0.00607)
gdp	0.0143***	0.00938**	0.0142***	0.0347***
	(0.00449)	(0.00407)	(0.000374)	(0.000132)
pop	0.0315***	0.0464*	0.0396***	0.00598***
	(0.00864)	(0.0272)	(0.00147)	(0.000207)
enr	0.00178***	0.00110***	0.000712***	0.000392***
	(5.27e-05)	(7.89e-05)	(1.09e-06)	(1.04e-06)
fdi	0.000679	0.000220	0.00188***	0.00172***
	(0.00213)	(0.00198)	(3.14e-05)	(1.88e-05)
tr	-0.00212	-0.00376	-0.00403***	-0.00129***
	(0.00201)	(0.00241)	(9.48e-05)	(7.74e-05)
L.co2			0.285***	0.810***
			(0.000639)	(0.000830)
Constant	-0.672	-0.00649		-0.301***
	(0.501)	(1.680)		(0.0131)
Observations	473	473	372	473
R-squared		0.448		
Number of id	98	98	96	98

Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Among the control variables, economic growth (GDP) exhibits a positive and statistically significant effect on CO_2 emissions across all estimation techniques. This finding suggests that economic expansion continues to rely heavily on carbon-intensive

production processes and energy systems within BRI countries. The result is consistent with the traditional Environmental Kuznets Curve literature, which argues that economic growth initially increases environmental pressure through higher resource consumption and industrial activity [20, 31]. Population growth also has a positive and significant impact on emissions. Larger populations increase demand for energy, transportation, housing, and industrial production, thereby contributing to environmental degradation. This finding supports the IPAT framework, which identifies population as a major determinant of environmental pressure [32]. Energy consumption remains the strongest and most consistent determinant of CO_2 emissions. The coefficient is positive and highly significant in all specifications, confirming that fossil-fuel-dependent energy systems continue to drive carbon emissions across BRI economies. This result is consistent with extensive empirical evidence linking energy use to environmental degradation [33].

The coefficient of trade openness is generally negative and becomes statistically significant in the dynamic specifications. This suggests that trade may contribute to lower emissions through technology transfer, improved production efficiency, and access to cleaner technologies. These findings support the technique-effect hypothesis proposed in the international trade and environment literature [35, 36]. Foreign direct investment (FDI) appears insignificant in the static models but becomes positive and significant in both GMM estimations. This result provides evidence supporting the pollution haven hypothesis, suggesting that foreign investment may increase emissions through the relocation of pollution-intensive activities to countries with less stringent environmental regulations [34].

Furthermore, the lagged dependent variable is positive and highly significant in both dynamic models, indicating strong persistence in CO_2 emissions over time. This finding justifies the use of dynamic panel estimation techniques and highlights the structural inertia associated with national energy systems and industrial development patterns. Overall, the baseline results support Hypothesis 1 and indicate that the digital economy currently contributes to higher carbon emissions across BRI countries.

4.3. Effects of Individual Digital Economy Indicators

To better understand the channels through which digitalization affects environmental quality, Table 4 examines the effects of individual digital economy indicators, including internet users (IUI), fixed broadband subscriptions (FBS), fixed telephone subscriptions (FTS), mobile cellular subscriptions (MCS), and secure internet servers (SI). The results reveal substantial heterogeneity across digital indicators. Internet usage becomes significantly negative in the dynamic specifications, suggesting that greater internet penetration contributes to emissions reduction. This finding may reflect efficiency gains generated through digital communication, e-commerce, teleworking, and the substitution of physical activities with virtual alternatives. Increased internet access can improve information dissemination and reduce transportation-related emissions, thereby enhancing environmental performance [27].

Fixed broadband subscriptions display mixed effects across models. While broadband expansion may initially increase energy demand due to infrastructure development, the negative coefficient observed in the System GMM specification suggests that broadband technologies eventually contribute to efficiency improvements and lower emissions as digital ecosystems mature. In contrast, fixed telephone subscriptions consistently exhibit a positive and significant effect on CO_2 emissions. This finding likely reflects the relatively lower efficiency of traditional communication technologies and their association with older infrastructure systems. Similarly, mobile cellular subscriptions are positively associated with emissions, particularly in dynamic specifications, indicating that rapid expansion of mobile networks increases electricity consumption and device-related energy demand.

The most environmentally beneficial digital indicator is secure internet servers, which consistently display a negative and highly significant relationship with CO_2 emissions. This result suggests that advanced and secure digital infrastructure supports efficient digital services, smart economic coordination, and technological innovation that contribute to lower environmental impacts. The finding highlights the importance of digital quality rather than merely digital quantity in promoting sustainable development. These results demonstrate that not all dimensions of digitalization have identical environmental consequences. While expansion-stage digital technologies may increase emissions, more sophisticated and secure digital infrastructure appears capable of supporting greener economic activities.

Table. 4. Effect of digital economy individual indicators models on co2 emission

	(1)	(2)	(3)	(4)
VARIABLES	co2	co2	co2	co2
iui	0.000597	-0.00733	-0.0142***	-0.00804***
	(0.00477)	(0.00449)	(0.000164)	(0.000192)
fbs	-0.0115	0.00815	0.0199***	-0.00182**
	(0.0148)	(0.0138)	(0.000928)	(0.000724)
fts	0.0239**	0.0267**	0.0382***	0.0145***
	(0.00993)	(0.0134)	(0.00143)	(0.000476)
mcs	0.000867	0.00131	0.00102***	0.00226***
	(0.00181)	(0.00170)	(0.000140)	(0.000110)
si	-0.000477***	-0.000620***	-0.000586***	-0.000199***
	(7.35e-05)	(6.67e-05)	(5.92e-06)	(4.81e-06)
gdp	0.0127***	0.00760**	0.0104***	0.0307***
	(0.00422)	(0.00364)	(0.000411)	(0.000214)
pop	0.0443***	0.0759**	0.0936***	0.00354***
	(0.00918)	(0.0309)	(0.00192)	(0.000561)
enr	0.00170***	0.00102***	0.000754***	0.000392***
	(5.20e-05)	(7.13e-05)	(2.03e-06)	(1.86e-06)
fdi	0.00201	0.00183	0.00301***	0.00193***
	(0.00202)	(0.00178)	(3.25e-05)	(0.000108)
tr	0.00249	0.00176	0.00211***	0.000590***
	(0.00206)	(0.00225)	(0.000109)	(0.000120)
L.co2			0.213***	0.820***
			(0.00194)	(0.00142)
Constant	-1.902***	-2.063		-0.468***
	(0.492)	(1.859)		(0.0222)
Observations	473	473	372	473
R-squared		0.567		
Number of id	98	98	96	98

Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

4.4. Nonlinear Effects of the Digital Economy

Table 5 investigates the nonlinear relationship between the digital economy and CO_2 emissions by incorporating the squared term of the digital economy index. The results provide strong evidence of a nonlinear relationship between digitalization and environmental degradation. In the System GMM specification, the linear term of the digital economy is positive and highly significant, whereas the squared term is negative and statistically significant. This combination of coefficients indicates an inverted-U-shaped relationship between digitalization and CO_2 emissions. In other words, digital development initially increases emissions but eventually contributes to environmental improvement after surpassing a critical threshold.

This finding supports the Digital Environmental Kuznets Curve (DEKC) hypothesis proposed in the literature [21–24]. During the early stages of digital transformation, investments in ICT infrastructure, data centers, communication networks, and digital devices increase electricity demand and carbon emissions. However, as digitalization advances, efficiency gains, technological innovation, smart resource management, and digital substitution effects become increasingly important, leading to lower emissions.

The results imply that the environmental consequences of digitalization depend largely on the stage of digital development. Countries at relatively low levels of digital maturity may experience rising emissions as digital infrastructure expands, whereas more advanced digital economies are likely to benefit from environmental improvements associated with technological efficiency and innovation.

The control variables maintain signs and significance levels largely consistent with the baseline models. GDP, population, and energy consumption continue to increase emissions, while trade openness contributes to environmental improvement through efficiency-enhancing channels. FDI remains positively associated with emissions in the dynamic specifications, reinforcing concerns regarding pollution-intensive investment patterns. Overall, the nonlinear analysis supports Hypotheses 2 and 3 and provides robust evidence for the existence of a Digital Environmental Kuznets Curve in BRI countries.

Table 5. Square term of digital economy.

VARIABLES	(1) co2	(2) co2	(3) co2	(4) co2
de	0.193	0.177	0.589***	0.0957***
	(0.190)	(0.268)	(0.00496)	(0.00441)
c.de#c.de	0.179**	0.449***	0.357***	-0.0225***
	(0.0789)	(0.0917)	(0.00134)	(0.00289)
gdp	0.0141***	0.00888**	0.0138***	0.0351***
	(0.00444)	(0.00395)	(0.000243)	(0.000189)
pop	0.0359***	0.0230	0.0193***	0.00534***
	(0.00887)	(0.0268)	(0.000625)	(0.000173)
enr	0.00177***	0.00108***	0.000749***	0.000385***
	(5.30e-05)	(7.67e-05)	(4.00e-07)	(9.32e-07)
fdi	0.000506	-4.52e-05	0.00149***	0.00186***
	(0.00211)	(0.00192)	(4.31e-05)	(1.40e-05)
tr	-0.00187	-0.00185	-0.00201***	-0.00114***
	(0.00201)	(0.00237)	(3.47e-05)	(5.25e-05)
L.co2			0.263***	0.813***
			(0.000287)	(0.000393)
Constant	-1.064**	1.017		-0.258***
	(0.533)	(1.644)		(0.0131)
Observations	473	473	372	473
R-squared		0.481		
Number of id	98	98	96	98

Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

4.5. Policy Implications

The findings offer several important policy implications. First, governments should promote energy-efficient digital infrastructure and encourage the use of renewable energy in data centers and communication networks. Second, policymakers should prioritize investments in advanced digital technologies and secure digital systems, which appear to generate environmental benefits. Third, environmental regulations should accompany digital expansion to prevent increases in emissions during the early stages of digital development. Finally, integrating digital transformation strategies with national climate policies can help ensure that digitalization contributes to long-term sustainable development and carbon-reduction objectives.

5. Conclusion

This study examined the impact of the digital economy on CO_2 emissions using a panel dataset covering multiple countries over the study period. The analysis employed pooled OLS, fixed effects, difference GMM, and system GMM estimators to ensure robustness and to address issues of unobserved heterogeneity, endogeneity, and dynamic persistence in emissions.

The empirical results provide consistent evidence that the digital economy significantly affects environmental outcomes. The baseline results show that digital development is generally associated with higher CO_2 emissions, reflecting the energy-intensive nature of ICT infrastructure, data usage, and digital expansion. However, when nonlinear effects are introduced, the results reveal a

more complex relationship. The squared term of the digital economy is significant and, in the dynamic specification, indicates a turning point where further digital development eventually reduces emissions. This supports the existence of a "digital Kuznets curve, " where early-stage digitalization increases emissions, but advanced digital economies contribute to emissions reduction through efficiency gains, technological innovation, and substitution of physical activities.

Across all models, GDP and population are consistently positive and significant, confirming that economic growth and demographic pressure remain key drivers of CO_2 emissions. Energy consumption also plays a dominant role in increasing emissions, highlighting the continued dependence on carbon-intensive energy systems. FDI shows a positive effect in dynamic models, suggesting that foreign investment may still be associated with pollution-intensive production in many countries. Trade openness generally exhibits a weak but often negative relationship with emissions, indicating potential gains from technology diffusion and efficiency improvements. Overall, the findings highlight that the environmental impact of digitalization is not uniform but depends on the level of digital development. While early stages of digital expansion may exacerbate emissions, more advanced digital economies can contribute to environmental improvement.

Despite these important findings, this study has several limitations. First, the measurement of the digital economy relies on available proxies, which may not fully capture all dimensions of digital transformation such as artificial intelligence adoption, cloud computing intensity, or digital service integration. Second, the study does not explicitly account for differences in environmental regulation, institutional quality, or energy policy across countries, which may influence the digital economy–emissions relationship. Third, although System GMM addresses endogeneity concerns, the validity of results depends on instrument selection, which may still introduce some bias.

Future research could extend this work by incorporating more granular indicators of digital transformation, such as AI adoption, digital services trade, or green digital technologies. In addition, future studies could explore sector-specific emissions to better understand how digitalization affects industry, transport, and services differently. Comparative studies between developed and developing countries, as well as regional analyses, would also provide deeper insights into heterogeneous effects. Finally, integrating institutional quality, environmental regulation, and green innovation into the framework could further clarify the channels through which the digital economy influences environmental sustainability.

Ethics approval/declaration: This study did not involve human participants, animal subjects, clinical materials, household surveys, interviews, experiments, or the collection of personal or sensitive data. The analysis was based entirely on secondary annual macroeconomic and electricity-sector time-series data for Sierra Leone covering 2000–2024, obtained from publicly available and official institutional sources, including the World Bank's World Development Indicators and relevant national electricity-sector institutions. Therefore, formal ethical approval was not required

Consent to participate: Not applicable

Consent for publication: Not applicable.

Author Contributions: Iqra: Conceptualization; Methodology; Data curation; Formal analysis; Investigation; Writing—original draft; Writing—review and editing. Khadija Ashfaq: Investigation; Validation; Writing—review and editing. Fahim Khan: Conceptualization; Methodology; Data curation; Formal analysis; Investigation; Writing—original draft; Writing—review and editing. All authors reviewed and approved the final version of the manuscript.

Funding: Not applicable

Data Availability Statement: All datasets used in this study are publicly available from the respective data providers. The constructed digital economy index (PCA-based) and the processed panel dataset may be obtained from the corresponding author upon reasonable request.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., ... & Park, Y. (2023). IPCC, 2023: Climate change 2023: Synthesis report, summary for policymakers. Contribution of working groups i, II and III to the sixth assessment report of the intergovernmental panel on climate change [core writing team, h. Lee and j. Romero (eds.)]. IPCC, geneva, Switzerland.
2. IEA, P. (2022). World energy outlook 2022. *Paris, France: International Energy Agency (IEA)*, *17*.OECD. Digital Transformation and the Environment. OECD Publishing, Paris, 2021.
3. Hou, J. (2025). Transforming energy for sustainability: The digital economy's role in reducing industrial hazards. *Energy Exploration & Exploitation*, *43*(5), 1916-1947.
4. Zhang, Y., Liu, X., & Yang, J. (2024). Digital economy, green dual innovation and carbon emissions. *Sustainability*, *16*(17), 7291.
5. Sadorsky, P. (2012). Correlations and volatility spillovers between oil prices and the stock prices of clean energy and technology companies. *Energy economics*, *34*(1), 248-255.
6. Shen, Y., Yang, Z., & Zhang, X. (2023). Impact of digital technology on carbon emissions: Evidence from Chinese cities. *Frontiers in Ecology and Evolution*, *11*, 1166376.
7. Pradhan, K. C., Mishra, B., & Mohapatra, S. M. (2024). Investigating the relationship between economic growth, energy consumption, and carbon dioxide (CO2) emissions: a comparative analysis of South Asian nations and G-7 countries. *Clean Technologies and Environmental Policy*, *26*(10), 3349-3367.
8. Wang, L., Ye, Z., & Li, C. (2025). Coordinated development of the digital economy and environmental quality: evidence from 285 Chinese cities. *Environmental Conservation*, *52*(4), 224-232.
9. Dinda, S. (2004). Environmental Kuznets curve hypothesis: a survey. *Ecological economics*, *49*(4), 431-455.
10. Su, X., Wang, S., & Li, F. (2023). The impact of digital transformation on ESG performance based on the mediating effect of dynamic capabilities. *Sustainability*, *15*(18), 13506.
11. Liu, X., Chen, L., Lu, Y., Chang, M., Xiao, Y., Yang, H., ... & Zhang, L. (2025). Research on the impact of the digital economy on carbon emissions based on the dual perspectives of carbon emission reduction and carbon efficiency. *Scientific reports*, *15*(1), 3416.
12. Education, O. E. C. D. (2021). Digital Transformation.
13. Liu, Y., Zhang, Y., Ren, S., Yang, M., Wang, Y., & Huisingh, D. (2020). How can smart technologies contribute to sustainable product lifecycle management?. *Journal of Cleaner Production*, *249*, 119423.
14. Trane, M., Marelli, L., Siragusa, A., Pollo, R., & Lombardi, P. (2023). Progress by research to achieve the sustainable development goals in the EU: a systematic literature review. *Sustainability*, *15*(9), 7055.
15. Usman, M., Radulescu, M., Balsalobre-Lorente, D., & Rehman, A. (2023). Investigation on the causality relationship between environmental innovation and energy consumption: Empirical evidence from EU countries. *Energy & Environment*, *34*(8), 3130-3159.
16. Sadorsky, P. (2012). Correlations and volatility spillovers between oil prices and the stock prices of clean energy and technology companies. *Energy economics*, *34*(1), 248-255.
17. Wang, N., Guo, Z., Shang, D., & Li, K. (2024). Carbon trading price forecasting in digitalization social change era using an explainable machine learning approach: The case of China as emerging country evidence. *Technological Forecasting and Social Change*, *200*, 123178.
18. Wang, Y., Li, Y., Suo, Y., Qiang, Y., Zhao, J., & Li, K. (2023). A scalable, efficient, and secured consensus mechanism for Vehicle-to-Vehicle energy trading blockchain. *Energy Reports*, *10*, 1565-1574.
19. Dinda, S. (2004). Environmental Kuznets curve hypothesis: a survey. *Ecological economics*, *49*(4), 431-455.
20. Lei, X., Ma, Y., Ke, J., & Zhang, C. (2023). The non-linear impact of the digital economy on carbon emissions based on a mediated effects model. *Sustainability*, *15*(9), 7438.
21. Wu, D. (2026). Digital economy, digital transformation of manufacturing enterprises, and carbon emission reduction. *International Review of Economics & Finance*, 105153.
22. Sun, X., Li, Z., & Guo, C. (2026). Low-carbon transition effects of the digital economy in Chinese cities—the perspectives of green technology innovation and energy efficiency. *Humanities and Social Sciences Communications*, *13*(1), 578.

23. Sun, Y., Li, M., Li, A., Wu, Y., Hu, W., & Ji, L. (2026). The resilience efficiency in the Chinese new energy production, storage, and application industries: a digital transformation perspective through dynamic range directional model directional distance function data envelopment analysis. *Humanities and Social Sciences Communications*.
24. Huang, J., Zheng, B., & Du, M. (2026). How digital economy mitigates urban carbon emissions: The green facilitative power of industrial coagglomeration. *Applied Economics*, *58*(18), 3457-3475.
25. Cheng, D., Zhao, Y., & Guo, Y. (2025). Research on the mechanism of digital–real economic integration enhancing industrial structure upgrading. *Economies*, *13*(9), 253.
26. Li, X., Lin, Z., & Cao, Y. (2026). Industrial internet platform–enabled supply chain low-carbon transformation: A two-stage evolutionary game approach. *International Journal of Production Economics*, 110162.
27. Hao, X., & Sun, Q. (2025). Impact of Information-Based New Infrastructure on Carbon Emissions: Evidence from Cross-Country Panel Data. *Journal of Information Economics*, *3*(2), 29-50.
28. Citaristi, I. (2022). International telecommunication union—itu. In *The Europa directory of international organizations 2022* (pp. 365-369). Routledge.
29. Crovato, D., & Rosania, J. (2026). Artificial Intelligence and Energy Overconsumption: Data Center Electricity Demand, Cooling Burdens, and Regional Sustainability Constraints. *Energy and Power Engineering*, *18*(4), 168-202.
30. Crovato, D., & Rosania, J. (2026). Artificial Intelligence and Energy Overconsumption: Data Center Electricity Demand, Cooling Burdens, and Regional Sustainability Constraints. *Energy and Power Engineering*, *18*(4), 168-202.
31. Ehrlich, P. R., & Holdren, J. P. (1971). Impact of Population Growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. *Science*, *171*(3977), 1212-1217.
32. Rej, S., & Nag, B. (2021). Investigating The Environmental Kuznets Curve (Ekc) Hypothesis For India: Does India Have Enough Capital To Supplement Renewable Energy Usage In The Correction of Carbon Emissions?.
33. Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. *Ecological economics*, *48*(1), 71-81.
34. Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment?. *American economic review*, *91*(4), 877-908.
35. Trane, M., Marelli, L., Siragusa, A., Pollo, R., & Lombardi, P. (2023). Progress by research to achieve the sustainable development goals in the EU: a systematic literature review. *Sustainability*, *15*(9), 7055.
36. Zhou, X., Zhang, J., & Li, J. (2013). Industrial structural transformation and carbon dioxide emissions in China. *Energy policy*, *57*, 43-51.

Copyright: © 2026 by the authors. Published by Science Research Publishers on behalf of the Journal of Environmental and Energy Economics. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC-ND) license.