DOI: 10.52131/pjhss.2026.v14i1.3070

Pakistan Journal of Humanities and Social Sciences

Volume 14, Number 01, 2026, Pages 20-26
Journal Homepage:
https://journals.internationalrasd.org/index.php/pjhss

PAKISTAN JOURNAL OF HUMANITIES AND SOCIAL SCIENCES (PJHSS)
INTERNATIONAL RESEARCH ASSOCIATION FOR SUSTAINABLE DEVELOPMENT

Do Digital Transformation and Renewable Energy mitigate CO_2 Emissions in SAARC Economies? A Dynamic Panel Data Analysis

Naveed Munir[1], Furrukh Bashir[2], Muhammad Atiq-ur- Rehman[3], Snober Fazal[4]

[1] Lecturer, Higher Education Department, Punjab, Lahore, Pakistan. Email: naveedmunir0420@gmail.com
[2] Associate Professor, Bahauddin Zakariya University, Multan, Pakistan. Email: furrukh@bzu.edu.pk
[3] Higher Education Department, Punjab & Superior University, Lahore, Pakistan. Email: atiq164@live.com
[4] Muhammad Nawaz Sharif University of Agriculture, Multan, Pakistan. Email: snoberfazal44@yahoo.com

ARTICLE INFO

Article History:
Received: October 02, 2025
Revised: February 21, 2026
Accepted: February 22, 2026
Available Online: February 23, 2026

Keywords:
Digital Transformation
Renewable Energy
CO2 Emissions
Economic Growth

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

To cope with the environmental challenges, developed and developing nations are taking different strategies. The application of digital technologies in various systems and the use of renewable energy can be helpful in reducing environmental pollution. Thus, the objective of this research work is to investigate the relationship between digital transformation (DT), renewable energy (RE), and carbon dioxide (CO_2) emissions in the South Asian Association for Regional Cooperation (SAARC) nations. To identify how the thing changes in the short and long run, we used a method called the system generalized method of moments (SGMM), after collecting data from 1985 to 2024. The results show that digital transformation and renewable energy reduce CO_2 emissions in SAARC nations. However, economic growth and population augment CO_2 emissions. To analyze the complex relationship between digital technology and renewable energy in coping with emissions, an interaction term is used. The positive and significant result of the interaction term shows that the positive effect of renewable energy on the environment is hampered as digital transformation is assisted by the generation of energy from fossil fuels. Moreover, the renewable energy consumption and digital transformation are substitutes for abating environmental pollution in the SAARC countries. This research work proposes that the SAARC countries should invest in digital transformation, renewable energy, and other eco-friendly technologies to reduce environmental emissions in the region.

Corresponding Author's Email: naveedmunir0420@gmail.com

1. Introduction

The developing economies with fast population growth, rapid economic activities, and high dependency on fossil fuels have become highly susceptible to environmental change. Environmental pollution has become a major challenge in South Asia, posing high-level risks to the environment. The repeated climate change negotiations emphasized the importance of slowing down global climate change. All nations are encouraged to enhance their mitigation actions to participate in the global efforts of reducing environmental pollution. The technological development and environmental regulations are thought to be important to reach the final stage of the environmental Kuznets Curve (EKC). Ecological damages may also be reduced by the use of renewable energy (Hou et al., 2023). In developing regions, like South Asia, access to costly, environmentally friendly technologies is difficult to attain due to financial constraints, whereas high-income countries have access to these technologies due to having sufficient funds.

Therefore, the poor growing economies still have to keep their production systems based on fossil fuels.

Energy consumption is very important in economic expansion, which is why the need for renewable energy to consume becomes a pivotal factor in environmentally friendly and sustainable economic growth. The SAARC countries have abundant resources that have the potential to promote economic development, but most countries have been facing challenge the CO_2 emissions due to the usage of these natural resources. Digital technology adoption has played a significant role in environmental sustainability. The use of digital transformation has become a vital factor for stimulating human welfare and sustainable growth. The usage of digital technologies is negatively correlated with environmental contamination; it is also helpful in improving the quality of life (Caglar, Balsalobre-Lorente, & Akin, 2021; Jie et al., 2023). Despite the reasonable economic performance of SAARC economies, their environmental sustainability record could have been more unsatisfactory. Therefore, it is very important to identify the factors that affect CO_2 emissions in these states and to devise a policy suggestion to reduce the environmental damage. The popularity of digital transformation in the current era has become a significant factor in improving environmental performance. Digital technologies, including internet infrastructure, ICT, and data-driven platforms, improve energy efficiency and optimize cleaner production processes. Digital transformation helps in low CO_2 emissions with smart grids and intelligent energy management systems. The use of digital transformation outcomes leads to sustainable economic behavior, like reducing the use of paper and reducing transportation, which ultimately leads to a reduction in environmental emissions.

Renewable energy plays a supportive role in attaining environmental sustainability. There is an extreme need for a reduction in the greenhouse gas emissions released by the fossil fuel-based energy resources (Adebayo & Kirikkaleli, 2021; Atiq-ur-Rehman et al., 2025). The South Asian region has immense potential for solar and hydropower resources. However, in the wake of increasing energy demand, the overall contribution of renewable energy is still not satisfactory in the South Asian region. Therefore, the need for assessing the impact of digital transformation on CO_2 emissions assumes significance in the wake of the extreme need for sustainable development in the South Asian nations. This research will help in understanding the effect of renewable energy consumption and digitalization on CO_2 emissions in the South Asian nations. The developing countries need energy consumption due to the increasing growth in economic activities (Mukhtarov, Yüksel, & Dinçer, 2022). The economic development activities of the South Asian countries are largely dependent on conventional fossil fuels, which is a threat to the environmental sustainability in the region (Canbay, 2021). Although the current research on digital transformation and renewable energy is largely carried out individually, their combined effect on environmental degradation is unclear, which reveals an area of concern that is largely unexplored, particularly in developing countries. On the one hand, digital transformation helps in the development of renewable energy services, thus improving the efficiency of the electric power sector. On the other hand, they can also assist in renewable energy production, along with a supportive part in energy demand management practices. However, digitalization can be energy-intensive, which may lead to an increased demand for energy. In other words, digital transformation leads to an increased demand for electricity, thus making digitalization an area of concern. Theoretically, if digital transformation is supported by fossil fuel-based energy generation, then the positive influence of renewable energy on the sustainable economy may be compromised. Hence, there is a complex nexus between digital technologies and renewable energy. They may be complements and or substitutes regarding environmental emissions.

2. Literature review

A large number of studies examine the significance of digital transformation and the consumption of renewable energy sources in CO_2 emissions, particularly in developing countries. Although global studies show that digital transformation causes a decrease in carbon emissions, the processes differ. A number of internal and external factors contribute to the development of unique transition approaches to renewable energy and environmental emissions. Most of the studies have focused on the positive effects of renewable energy on environmental emissions (Murshed, 2021; Nazir et al., 2018). The EKC theory emphasizes the importance of renewable energy in environmental sustainability (Naqvi et al., 2021; Tariq & Hassan, 2023). In the last few years, green projects have accelerated to achieve the Sustainable Development Goals (SDGs). The projects have focused on wind and solar energy projects, stressing the importance of green strategic approaches in the decarbonization of economic activities (Khezri, Heshmati, &

Khodaei, 2022; Rafique et al., 2021). In the wake of the increasing number of ecological challenges, it is necessary that we continue to focus on environmentally responsible policies. The environmental policy and research have been identified as one of the most important supporting elements for ecological sustainability, resulting in an environmentally friendly future. According to Nawaz et al. (2021), renewable energy is a general term focusing on financial investment in favor of sustainability initiatives and eco-friendly policies. Cai et al. (2022) carried out a study on South Asian nations and concluded that there is a weak relationship between renewable energy and the environmental footprint of the region. Meo and Abd Karim (2022) analyzed the effects of renewable energy on the ecological footprint of the economies with the highest financial investment in renewable energy(Ragmoun & Alfalih, 2025; Ragmoun & Ben-Salha, 2024). An indirect proportionality relationship between renewable energy and ecological sustainability has been discovered in the nations under consideration. From the above results, it can be concluded that renewable energy is an efficient approach for ecological conservation.

In recent years, the adoption of digital technology or digital transformation has gained enormous popularity, with an unprecedented rise in digitalization in the business, government, and individual sectors. Fryer (2019) described two possible approaches of digital technologies in reducing environmental emissions: digital technology can do this by improving energy efficiency. From an economic viewpoint, digital technology is extremely efficient in reducing emissions. Digital technology provides a ray of hope in realizing sustainability because of several reasons (Ahmed, 2016). Murshed (2021) analyzes the effect of digitalization policies on the reduction of emissions in South Asian economies. It has been revealed that industries based on natural resources become more productive and contribute to greening. In addition, the effectiveness of institutional quality and the control of urbanization can counteract the deterioration of environmental quality. Clean energy is an important element in the digital technology industry, according to (Youssef, Boubaker, & Omri, 2020). Haq et al. (2024) analyze the effect of renewable energy, globalization, technological innovation, and GDP on environmental emissions in SAARC countries. The empirical results show that renewable energy has a positive effect on reducing CO_2 emissions. Some time series studies indicate that the growth of the digital economy helps in decreasing carbon emissions in general(Dler M Ahmed, Z Azhar, & Aram J Mohammad, 2024; Dler Mousa Ahmed, Zubir Azhar, & Aram Jawhar Mohammad, 2024). For instance, Huang and Wu (2024) conducted empirical research based on the provincial panel data of China, which indicates that the digital economy helps in reducing carbon emissions by means of innovation and structural transformation towards low-carbon production methods. Ma & Li (2025) explain that the digital economy helps reduce emission intensity by means of energy transformation and industrial upgrading. Moreover, research on G-20 economies indicates that digital technologies enhance energy efficiency and support low-carbon emissions.

3. Empirical Methodology

3.1. Overview of variables and data sources

The data on CO_2 emissions, renewable energy, GDP growth, population, and trade openness have been obtained from the World Development Indicators (WDI) database. The number of individuals using the internet has been used as a proxy for digital technology, which is also obtained from WDI. Internet usage and mobile phone subscriptions on mobile phones have been employed as a proxy for digital technology (Khan, Oubaih, & Elgourrami, 2022). The chosen indicators with symbols, measurements, and data sources are shown in Table 1.

Table 1: Data Sources

Indicators	Symbol	Measurement	Source
CO_2 emissions	CO_2	Carbon dioxide (CO_2) emissions (% change from 1990)	WDI
Renewable energy	RE	Renewable energy consumption measured in kilotons (kt)	WDI
Digital technology	DT	Internet users as a percentage of total population	WDI
Economic growth	GDP	GDP per capita (constant 2010 USD)	WDI
Trade	Trade	Trade as a percentage of GDP	WDI
Population	POP	Population growth (%)	WDI

3.2. Model Specification

The econometric model used in this research can be stated mathematically as given below.

$$CO_{2\,it} = f\,(DT_{it,}\,, ,RE_{it,}\,,\ GDP_{it},\ ,\ TRADE_{it,}\,,\ POP_{it})$$

The System-GMM Equation can be written as

$$\ln CO_{2,it} = \alpha \ln CO_{2,i,t-1} + \beta_1 \ln DT_{it} + \beta_2 \ln RE_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln TRADE_{it} + \beta_5 \ln POP_{it} + \mu_i + \varepsilon_{it}$$

The System-GMM Equation with Interaction Term can be expressed as follows

$$\ln CO_{2,it} = \alpha \ln CO_{2,i,t-1} + \beta_1 \ln DT_{it} + \beta_2 \ln RE_{it} + \beta_3 (\ln DT_{it} \times \ln RE_{it}) + \beta_4 \ln GDP_{it} + \beta_5 \ln TRADE_{it} + \beta_6 \ln POP_{it} + \mu_i + \varepsilon_{it}$$

Where β_3 is an interaction term to represent complementarity or the rebound effect. If $\beta_3 < 0$, It means DT enhances the pollution-reducing role of RE. Conversely, if $\beta_3 > 0$, it represents the dominance of scale/rebound effects. The term μ_i represents unobserved country-specific heterogeneity and ε_{it} is an idiosyncratic error term. The System GMM approach is adopted for the estimation as it is a useful approach to control for the potential endogeneity in the empirical model.

4. Empirical Results

The empirical results are provided in the following tables.

Table 2: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2	280	238.806	588.787	.056	3153.829
DT	207	15.757	22.037	0	88.426
RE	226	53.882	28.617	1.2	95.9
GDP	279	5.352	4.837	-32.909	37.508
TRADE	245	51.794	30.134	12.219	165.979
POP	280	1.652	1.06	-4.08	3.54

Table 3: Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) CO_2	1.000					
(2) DT	-0.069	1.000				
(3) RE	-0.364	-0.346	1.000			
(4) GDP	0.049	-0.071	-0.043	1.000		
(5) TRADE	-0.232	0.526	-0.058	0.160	1.000	
(6) POP	-0.057	-0.063	-0.238	0.005	0.146	1.000

Table 4: System GMM

CO_2	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]
CO_2 (-1)	1.031***	.003	372.57	0	1.026	1.036
DT	-.217**	.102	-2.12	.034	-.416	-.017
RE	-.198*	.101	-1.96	.05	-.397	0
GDP	1.123***	.332	3.38	.001	.471	1.774
TRADE	.052	.084	0.62	.537	-.113	.216
POP	5.164	3.641	1.42	.156	-1.972	12.299
Mean dependent var	292.316		Number of obs.		171	

*** p<.01, ** p<.05, * p<.1

Table 5: System GMM

CO_2	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]
CO_2 (-1)	1.032***	0.003	393.90	0.00	1.026	1.037
DT	-1.186***	0.228	-5.19	0.00	-1.633	-0.738
RE	-0.505***	0.106	-4.75	0.00	-0.713	-0.297
DTRE	0.016***	0.004	4.44	0.00	0.009	0.023
GDP	1.215***	0.327	3.72	0.00	0.575	1.856
TRADE	0.333***	0.091	3.66	0.01	0.154	0.511
POP	8.279***	2.535	3.27	0.001	3.31	13.247
Mean dependent var	292.316		Number of obs		171	

*** p<.01, ** p<.05, * p<.1

(with interaction term)

5. Interpretations and Findings

Table 2 displays the descriptive statistics for all the variables used in our empirical analysis. The dispersion of variables is high, with a large standard deviation, varied means, and a wide gap between minimum and maximum values. Hence, there exists a strong heterogeneity across countries. Table 3 demonstrates the correlation matrix among the variables of our model. CO_2 emissions are negatively correlated with digital technology, trade openness, renewable energy, and population, while showing a weak positive correlation with economic growth. The relatively robust negative correlation between CO_2 emissions and renewable energy suggests that higher reliance on renewable energy leads to lower emissions. Digital technology is negatively correlated with renewable energy and economic growth, but positively correlated with trade openness, indicating that more digitally connected countries tend to be more integrated into world trade. Renewable energy exhibits a fragile correlation with most of the control variables, implying its independent role in explaining ecological outcomes. Prominently, none of the correlation coefficients is very high. Table 4 displays that the coefficient of CO_2 emissions, when incorporated in the model in a lagged form, is positive and significant. It indicates that CO_2 emissions have a persistent effect over time. Such types of attributes usually emerge due to the slowly-changing nature of energy infrastructure and technology. Digital technology has a significant and negative effect on CO_2 emissions, which is statistically significant at 5%. This indicates that with the improved aspects of internet penetration or internet connectivity, CO_2 emissions reduce. This thus provides an argument for digital transformation and its positive impacts on energy conservation, information flows, and its potential to promote cleaner consumption patterns. Similarly, renewable energy has a negative and marginally significant effect on CO_2 emissions, which indicates that renewable energy helps reduce environmental pollutants due to its adoption as a better source of energy. GDP growth has a positive and significant effect on CO_2 emissions, which shows that economic growth in such economies is still positively related to increased CO_2 emissions due to increased growth pattern.

This finding also supports the EKC notion in SAARC countries. Trade openness and population growth have a positive but insignificant impact, which can be explained as the impact of these variables is relatively less significant once other factors are considered. Overall findings indicate a higher relative importance of digital transformation and renewable energy sources in reducing CO_2 emissions in SAARC countries. Table 5 presents the System GMM estimation results after incorporating interactions between digital technology and renewable energy to ascertain their joint impact on CO_2 emissions. As presented in Table 5, the lagged dependent variable is positive and significant, which confirms persistence in emissions and shows that the current values of CO_2 emissions are significantly affected by their past values. Digital Technology (DT) and Renewable Energy Consumption (RE) both individually contribute negatively and significantly towards CO_2 emissions. The relatively larger size of these coefficients as compared to the baseline model indicates the relative importance of digitalization and renewable energy, individually and jointly, in controlling and reducing environmental pollution. This also indicates the relative significance of improving internet penetration or digital transformation in ecological sustainability. However, we find a positive and significant value for the interaction term (DT x RE), indicating that the marginal emission-reducing impact of digital technology diminishes as renewable energy usage increases, and vice versa. It does not imply any pro-environment effect but rather a situation of marginal decreasing returns when both variables are jointly increased. In economies where renewable energy transformation is already high, additional digitalization may lead to increased fossil-based energy demand. The effect of economic growth remains positive and significant, showing that GDP growth is still a costly process in terms of environmental damages in these sampled countries. Meanwhile, trade openness and population also emerge as positive and statistically significant factors, suggesting that these two elements contribute to increased emissions even at the interaction level. Overall, the findings here suggest that although digital transformation and cleaner energy are significant in reducing emissions, their interaction reveals a complex relationship between these two.

6. Conclusion

This study evaluates the impact of digital transformation and renewable energy on environmental pollution. We also inspect the interaction between digital transformation and renewable energy in environmental sustainability, while considering the impact of economic growth, trade, and population in the SAARC nations. To account for the endogeneity, the System GMM method has been employed for estimation. The empirical findings indicate a high degree of persistence in CO_2 emissions, which clearly shows that environmental degradation is a long-run process and path-dependent in nature for the SAARC nations. Digital transformation and renewable energy have been identified as the prominent factors in reducing environmental pollution, and the coefficients are individually negative and statistically significant. The empirical findings support the fact that digital transformation promotes energy efficiency, cleaner production methods, and better monitoring of the environment, while renewable energy reduces the reliance on fossil fuels, which in turn reduces the intensity of CO_2 emissions. With the addition of the interaction term between digital transformation and renewable energy, we observe that there is a complex relationship between the two variables. The positive interaction term indicates a diminishing marginal effect in the joint increase, which may be attributed to the rebound effects or the inability to meet the growing demands for electricity consumption in the digital transformation process. This indicates that a digital transformation requires more energy, which can increase environmental degradation if fossil fuels are employed for energy production. In addition, economic growth, openness to trade, and population growth have strong impacts on CO_2 emissions, indicating accelerated growth and globalization processes in the sampled countries. In conclusion, the above results indicate the importance and need for an integrated policy framework that focuses on the promotion of digital transformation and green growth. The population control, along with green growth strategies, is also an important policy framework that should be followed for environmental sustainability. The digital transformation using renewable energy will be helpful for the sustainable future of SAARC economies.

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