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TECHNOLOGICAL, DIGITAL, AND ENERGY TRANSITIONS TOWARDS ENVIRONMENTAL SUSTAINABILITY: EVIDENCE FROM SOUTH ASIAN ECONOMIES

Dr. Muhammad Nadeem[1], Maimoona Javed[2], Dr. Madeeha Rauf[*3], Syeda Iqra Zainab[4]

[1]*Assistant Professor, Department of Computer Science, National University of Modern Languages, Islamabad, Multan Campus.*
[2]*School of Economics, Bahauddin Zakariya University, Multan, Pakistan.*
[*3]*Assistant Professor, NFC Institute of Engineering and Technology, Multan, Pakistan.*
[4]*Institute of Social Sciences, Bahauddin Zakariya University, Multan, Pakistan.*

[*1]mnadeem@numl.edu.pk, [2]maimoonajaved1987@gmail.com, [*3]madeeharauf@gmail.com, [4]iqrashah55524@gmail.com

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Corresponding Author: *
Dr. Madeeha Rauf

Abstract

This study examines the long-run determinants of environmental sustainability in five South Asian economies by investigating the effects of technological innovation, digitalization, renewable energy, economic growth, and total resource rents on CO_2 emissions. Using panel data and FMOLS and DOLS estimators, the findings reveal that technological innovation, digitalization, and renewable energy significantly reduce CO_2 emissions, thereby improving environmental sustainability. In contrast, economic growth and total resource rents pointedly increase CO_2 emissions, indicating persistent environmental pressures from economic expansion and resource-dependent activities. The consistent coefficient signs across FMOLS and DOLS confirm the robustness of the long-run relationships. The findings suggest that South Asian economies should accelerate green technological innovation, digital transformation, renewable-energy adoption, and environmentally sustainable economic diversification while strengthening environmental regulations for resource-intensive activities.

INTRODUCTION

Developing economies' growing reliance on natural systems, driven by rapid economic growth, industrialization, and urbanization, is putting significant pressure on these ecosystems. CO_2 emissions are a major source of greenhouse gas accumulation and depend on the amount of fossil fuel used to produce and use products. As such, South Asian economies need to achieve economic growth without further degrading the environment or moving away from the United Nations' Sustainable Development Goals. As environmental pressures in South Asia increase, the demand for technology and energy-based alternatives to develop economies more

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sustainably has grown significantly. Thus, technological innovation, digitalization, renewable energy, economic growth, and natural resource use are key factors in how environmentally successful South Asian nations are.

Technological innovation can help create a more environmentally sustainable economy by enabling better production practices and efficiency improvements, reducing waste from inefficient production, and encouraging companies to adopt cleaner production methods and technologies. Research in South Asian economies shows that technological innovation and related developments in energy use can reduce negative environmental impacts; however, the magnitude and direction of these impacts vary across countries (Examining Technical Factors Contributing to Carbon Emissions Management in South Asian Economies, 2023). Additionally, Qing et al. (2024) concluded that technological innovation and renewable energy can reduce environmental degradation in South Asian countries. However, the authors also noted that the same factors that could cause environmental degradation (natural resources) could increase it when combined with globalization. Digitalization has emerged as another area of significance because digital technology can enable better decision-making on resource allocation and production efficiency, support smart energy management, and encourage a shift to more sustainable economic systems. Murshed (2024) stated that digitalization can slow the growth of carbon emissions in South Asia and weaken the link between natural-resource dependency and increased carbon emissions. While digitalization does not inherently improve environmental performance, digital infrastructure consumes energy and materials; thus, the extent to which digital technologies yield positive environmental outcomes depends on how they are incorporated into production and energy systems.

Economic growth and natural resource dependence create additional challenges for environmental sustainability. Economic expansion can increase industrial production, transportation, energy consumption, and resource use, particularly in economies that remain strongly dependent on conventional energy sources. Recent evidence from South Asian countries indicates that economic development can increase environmental pressure, while renewable energy and technological innovation can help mitigate these effects (Farooq et al., 2024). Natural resource rents are similarly important because resource extraction can generate substantial economic benefits while simultaneously increasing environmental pressure when extraction and associated production activities rely on environmentally intensive technologies. Qing et al. (2024) demonstrate that natural-resource utilization increases ecological degradation in South Asian economies, highlighting the importance of managing resource dependence within broader environmental strategies. More recent evidence also suggests that digitalization, natural resource dependence, and renewable energy can affect CO_2 emissions in South Asia differently, emphasizing the need to examine these factors jointly rather than in isolation (Imran et al., 2026). Thus, the environmental consequences of economic growth and resource utilization may depend substantially on the technological and energy structure through which economic activities are undertaken.

Although a growing body of literature examines the environmental effects of technological innovations, digitalization, renewable energy, economic expansion, and natural resources, some important areas have received relatively little research. Many existing studies have analyzed single factors (or a few) and only a few combinations, while the interaction effects of all of these variables simultaneously over an extended period within a single systematic framework remain relatively understudied. The structural differences, resource bases, technological capabilities, and energy systems of the various countries in South Asia also mean that assuming

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identical effects for each country is likely inaccurate. The present study finds statistically significant cross-sectional dependence and slope heterogeneity among the variables. These findings indicate that the South Asian economies are connected by links of interdependence, while they do not share similar linkages. Additionally, Westerlund's findings support a long-run cointegration relationship among technological innovation, digitalization, economic growth, renewable energy, resource rents, and CO2 emissions. Thus, examining these indicators in a context that includes cross-country dependence, heterogeneity, and long-run interactions will provide evidence on sustainable environmental development in this area.

This research is an examination of how technological innovations, the extent of digitalization, economic growth, and renewable energy, as well as the level of total resource rents, influence environmental sustainability in five South Asian countries: Bangladesh, India, Nepal, Pakistan and Sri Lanka from 1995 through 2025. This study contributes to previous research by jointly examining factors such as technology, digitalization, the economy, energy, and resources that determine CO_2 emissions within a single South Asian context. Methodologically, before analyzing long-run cointegration and estimating long-run relationships using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), we first test for cross-sectional dependence and slope heterogeneity. Our empirical results indicate that technological innovation, digitalization, and renewable energy negatively affect CO_2 emissions. Conversely, our results also indicate long-run positive effects of economic growth and total resource rents on CO_2 emissions in both FMOLS and DOLS estimates. These results suggest that technological and digital advancements, along with renewable energy expansion, can support sustainable environmental policies. Furthermore, our empirical results show that economic growth and reliance on natural resources may lead to negative environmental impacts; therefore, policymakers should consider environmental regulations alongside economic development in South Asian nations.

2. Literature Review

2.1 Technological Innovation and Digitalization towards Environmental Sustainability

Technological innovation provides an ever-growing number of pathways to improve environmental sustainability. Technology increases production efficiency, reduces energy use, enables "cleaner" production processes, and supports a shift from harmful to less harmful technologies. Directed Technical Change theory supports the idea that technology can be developed towards "green" or cleaner uses if sufficient financial incentives and environmental regulations are in place (Acemoglu et al. 2012). Additionally, Popp (2002) shows that energy costs and available technology will induce energy-efficient innovation. Therefore, technological innovation may help reduce environmental degradation by giving developing-country economies the opportunity to increase output using less energy and fewer materials.

However, empirical evidence does not show a universally negative relationship between technological innovation and environmental degradation. The direction of influence may vary depending on the type of innovation, the economy's technological structure, the energy systems currently in use, and the level of economic development. For example, technological innovation may significantly increase efficiency; however, these gains may also drive higher production and consumption, creating potential rebound effects. Farooq et al. (2024) found heterogeneous results on how green technological innovation affected emissions in Pakistan, Bangladesh, India, Nepal, and Sri Lanka. Some countries saw decreased emissions due to green technological innovation, while others saw increased emissions. Qing et al. (2024), like Farooq et al. (2024), identified technological

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innovation as a primary factor contributing to ecological sustainability in South Asia, alongside renewable energy and natural resources. This research indicates that the environmental impact of technological innovation depends on the specific context.

The increasing presence of digitalization has become a new aspect of technology-driven change. Smart energy systems, digital tracking, intelligent transportation, better resource utilization, electronic transactions rather than paper-based transactions, and more efficient production and distribution networks can support many forms of environmental sustainability (Feroz et al., 2021). Despite this, the literature concerning empirically measured relationships is contradictory. For example, Lee and Brahmasrene (2014) have identified that increases in information and communication technology (ICT) in ASEAN countries have led to an increase in both economic growth and carbon dioxide (CO_2) emissions. Consequently, it appears that the initial phase of digital development could lead to greater levels of environmental pressure due to increased levels of consumption associated with increased energy usage. On the other hand, Asongu et al. (2017) have shown that ICT can interact with the environmental-sustainability relationship in a variety of ways based upon the degree of ICT penetration. More recently, Saia (2023) has demonstrated that the association between digitalization and CO_2 emissions will vary based upon the degree of research and development (R&D), with digitalization leading to lower levels of CO_2 emissions at high degrees of R&D. Additionally, Kopp et al. (2023) have identified that digitalization can lead to reduced CO_2 emissions; however, the difference between firm and household digitalization varies significantly. Furthermore, Charfeddine and Umlai's (2023) systematic review of 166 studies indicates that many empirical studies report positive associations between digitalization and environmental outcomes. However, these studies also highlight significant methodological limitations and an overreliance on linear statistical models.

Collectively, these findings indicate that technological innovation and digitalization do not inherently represent an automatic form of environmental sustainability. Rather, their impacts depend on whether they generate sufficient efficiencies to offset the additional energy and resource demands associated with them. Therefore, given the simultaneous presence of industrialization, energy use, and rapid digitalization across South Asia, empirical investigations into the interrelatedness of technological innovation, digitalization, and environmental sustainability using country-level data over extended time frames are warranted.

2.2 Renewable Energy and Environmental Sustainability

Transitioning from traditional fossil fuel-based energy systems to renewable energy is a critical strategy for mitigating environmental damage. Solar, wind, hydro power, and biomass have relatively low direct CO_2 emissions compared with their fossil fuel counterparts; thus, they can help reduce the carbon intensity of economic activities. Researchers have studied the interaction between renewable energy and economic development. Using a sample of OECD member states, Apergis and Payne (2010) found evidence of a long-run association between renewable energy use and GDP growth. In addition, Apergis and Payne (2010) demonstrated bi-directional causality between renewable energy consumption and economic growth. Similarly, Pao and Fu (2013) demonstrated the importance of renewable energy in Brazil's energy-GDP relationship. This suggests that renewable energy may contribute to sustainable development while facilitating the transition to cleaner energy (Khan et al., 2023; Abidin et al., 2026; Sheikh et al., 2026).

Many empirical studies support the environmental benefits of renewable energy. Within an extended Environmental Kuznets Curve (EKC) framework, Bilgili et al. (2016) demonstrate that renewable

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energy usage is positively correlated with reduced CO_2 emissions. Additionally, Acheampong et al. (2019) show that renewable energy effectively mitigates carbon emissions across all of Sub-Saharan Africa. In South Asia, Batool et al. (2022) examined six developing countries in East and South Asia and found that renewable energy positively affects environmental quality in both the short and long term; however, increased ICT use negatively affects environmental quality in the long term. Finally, for China, Jiang et al. (2022) demonstrate that the relationship between renewable energy use and CO_2 emissions is asymmetrical in both the short and long term; therefore, increases and decreases in renewable energy do not always have equivalent environmental impacts. Similarly, Zeb et al. (2014) examined five countries located in South Asia, including Bangladesh, India, Nepal, Pakistan and Sri Lanka. They used econometric techniques to analyze the causal relationships between renewable energy use, economic growth, environmental degradation and resource depletion.

Although renewable energy-environment linkages vary across countries and methods, differences in energy mix, technology, institutional quality, and the scale of renewable energy adoption may affect how renewable energy impacts the environment. The broader literature has shown that renewable energy can have varying impacts at different stages of development and based on the overall structure of the energy system. Balsalobre-Lorente et al. (2018) show that renewable electricity will improve environmental quality; however, economic growth could add to environmental pressures. Therefore, renewable energy should be viewed not just as an energy substitution process, but as part of a larger transformation in how goods and services are produced and consumed. Huang et al. (2023) provided additional empirical evidence from China regarding renewable energy through the lens of both natural resource rents and urbanization. Their results indicated that renewable energy positively affected environmental conditions, while natural resource rents significantly contributed to environmental degradation. These results highlight renewable energy's potential to counter the environmental pressures associated with resource-dependent development.

2.3 Economic Growth and Natural Resource Rents towards Environmental Sustainability

The link between increased incomes (i.e., economic growth) and increased environmental degradation (e.g., air pollution, climate change, etc.) has long been described by the Environmental Kuznets Curve (EKC) hypothesis. Initially, it was hypothesized that, until some point at which environmental damage would exceed what higher income levels could afford (the "environmental turning point"), pollution would rise as income rose. Studies such as those by Selden and Song (1994) support this inverted-U relationship between environmental degradation and economic development. Nevertheless, considerable disagreement remains over whether this inverse relationship exists in reality because the relationship between income and pollution appears to vary significantly by pollutants, countries, time period, and modeling approach (Stern, 2004). Moreover, Copeland and Taylor (2004) argue that environmental impacts associated with economic development depend on three distinct factors: scale (i.e., the size of the economy); composition (e.g., the mix of industries within the economy); and technique (e.g., how goods are produced). Thus, while economic growth may increase CO_2 emissions if a significant portion of the output increase comes from energy-intensive processes, these negative environmental impacts should ultimately lessen as an economy transitions to low-carbon technologies (Balsalobre-Lorente et al., 2018). In South Asia, Li and Yang (2023) report that GDP increases carbon emissions in India, Bangladesh, Pakistan, and Sri Lanka, while the environmental consequences of natural resources vary by resource type. Similarly, Safdar et al. (2022) show that natural-resource rents matter for both economic and

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environmental sustainability in South Asian economies. These findings indicate that economic expansion alone does not necessarily guarantee environmental improvement.

Natural resource rents offer yet another dimension to the interrelationship between economic development and environmental sustainability. On one hand, extracting natural resources can provide governments with increased revenue streams, create jobs, attract investments, stimulate economic activity, and generate revenue for governments. However, these activities often increase environmental pressure through extraction, processing, transportation, energy consumption, etc. In this context, Huang et al. (2020) conducted a case study in 25 developing Asian countries regarding forest resources, mineral resources, and oil extraction in relation to natural-resource rents and economic development. Based upon their research, they demonstrated that all three types of natural-resource rents contribute to economic development, thereby demonstrating the importance of dependence on natural resources for developing Asian economies. Additionally, Ullah et al. (2021) found a non-linear relationship between renewable energy production, natural-resource rents, and ecological footprint, which indicates that the environmental effects of natural-resource rents can differ based upon the stage of development. Furthermore, Huang et al. (2023) contributed additional evidence on the environmental impact of the resource curse in relation to natural-resource rents, renewable energy production, and urbanization in China. Their findings indicated that natural-resource rents are a key driver of environmental degradation, while renewable energy has contributed to improved environmental sustainability. Therefore, the authors emphasized that renewable energy development may effectively mitigate the negative environmental impacts of resource-dependent economic activities. Lastly, Wang et al. (2024) reinforced the importance of managing natural resources in South Asia, while Rana (2025) found that different types of resource rents generate different implications for sustainable development. Ultimately, it is not possible to consider resource rents solely as having positive or negative environmental impacts; rather, the outcomes depend upon how the resources were extracted, managed by whom and how the proceeds from the sale of the resources were allocated.

2.4 Research Gap

The existing literature provides substantial evidence regarding the individual relationships between technological innovation, digitalization, renewable energy, economic growth, natural resources, and environmental degradation. However, several gaps remain. First, researchers often examine technological innovation and digitalization separately, despite their growing interaction in modern production systems. Second, much of the digitalization literature has focused on developed economies or broad country panels, while evidence for South Asian economies remains comparatively limited. Charfeddine and Umlai (2023) specifically identify a lack of sufficiently developed empirical analysis of the pathways through which digitalization affects environmental sustainability. Third, existing South Asian studies often examine renewable energy, economic growth, natural resources, or technological innovation in separate models rather than integrating these determinants into a single long-run framework.

Fourth, the empirical literature produces heterogeneous findings. For example, ICT has been found to increase CO_2 emissions in some developing-country settings but reduce emissions under particular technological or research and development (R&D) conditions (Lee & Brahmasrene, 2014; Saia, 2023). Similarly, natural resources can intensify or mitigate environmental degradation depending on the resource type and institutional context (Balsalobre-Lorente et al., 2018; Li & Yang, 2023). Finally, the South Asian environmental literature has given relatively

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limited attention to cross-country dependence and slope heterogeneity. This is particularly relevant to the present study because the preliminary analysis confirms significant cross-sectional dependence and slope heterogeneity among the variables. The present study addresses these gaps by jointly examining technological innovation, digitalization, renewable energy, economic growth, and total resource rents in Bangladesh, India, Nepal, Pakistan, and Sri Lanka from 1995 to 2025, while explicitly accounting for cross-sectional dependence, slope heterogeneity, and long-run cointegration. The resulting framework provides a more integrated assessment of the technological, energy, economic, and resource-related determinants of environmental sustainability in South Asia.

3. Data Sources, Model and Methodology

In this study, data from 5 South Asian economies from 1995 to 2025 are used to analyze the impact of technological innovation (TEI), digitalization (DIGI), clean energy as renewable energy (REN), economic growth (ECR), and total resource rents (TRR) on environmental sustainability (ENS). To analyze the effect of digitalization and clean energy on environmental sustainability, the countries are selected based on the availability of data on digitalization and clean energy, as follows: Bangladesh, India, Nepal, Pakistan, and Sri Lanka.To measure environmental sustainability (ENS), CO_2 emissions (Kt) are used. In addition, the core independent variables are technological innovation (TEI), measured by the number of patent applications; economic growth (ECR), measured as GDP in constant 2015 US$; and digitalization (DIGI), measured as Mobile cellular subscriptions per 100 people. The model also includes renewable energy as clean energy (REN) as a percentage of total energy and total resource rents (TRR) as a percentage of GDP. The World Development Indicators are used to collect data on South Asian economies. Below is the functional form and baseline equation developed:

$$ENS = (TEI, DIGI, ECR, REN, TRR) \quad (1)$$

$$ENS_{it} = \beta_0 + \beta_1 TEI_{it} + \beta_2 DIGI_{it} + \beta_3 ECR_{it} + \beta_4 REN_{it} + \beta_5 TRR_{it} + \varepsilon_{it} \quad (2)$$

Where ENS indicates carbon dioxide emissions, TEI represents technological innovation, DIGI represents digitalization, ECR represents gross domestic product, REN represents clean energy, TRR indicates natural resource rents, and ε_{it} is the error term. The description of variables is given below in Table 1.

Table 1: Description of Variables

Signs	Description and Unit of Measurement	Sources
ENS	CO_2 Emissions (kt)	WDI
TEI	Number of patent applications (Residents + Non-residents)	WDI
DIGI	Digitalization (Mobile cellular subscriptions per 100 people)	WDI
ECR	Gross domestic product (Constant 2015 US$)	WDI
REN	Renewable Energy as Clean Energy (% of total energy consumption	WDI
TRR	Total natural resources rents (% of GDP)	WDI

Source: World Development Indicators of the World Bank.

We apply different panel data estimation techniques to assess the effect of TEI, DIGI, ECR, REN, and TRR on ENS in South Asian economies. Firstly, the cross-sectional dependence (CD) analysis is used. Second, we conduct a slope homogeneity (SH) test. Third, we examine long-run cointegration using the Westerlund cointegration test. Fourth, the FMOLS and DOLS

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models are applied to estimate parameters. The description of these techniques is given as follows: Validating the occurrence of possible common correlation effects on variables is the goal of the cross-sectional dependence (CD) test. The estimation outcomes may be impacted if CD is ignored in panel data. In this instance, cross-section dependence is verified by using the CD test to see whether the various variables are dependent on one another. CD test to address the problem of CD is as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1} \nu_{ij} \quad (3)$$

In the above equation (3), T and N indicate time, and the panel, ν_{ij} recognizes the correlation coefficient. The test is based on the following hypothesis:

H_o: Absence of CD
H_1: Presence of CD

After examining the CD test, the next important step is slope homogeneity (SH) between the cross-sections. Because the demographic and economic systems of the South Asian countries differ, the heterogeneity problem is crucial and SH provides panel estimators' consistency. The following equation tests the SH statistic:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}} (2k)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - k \right) \quad (4)$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}} \left(\frac{2k(T-K-1}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - k \right) \quad (5)$$

In above equations, $\tilde{\Delta}_{SH}$ Indicate the delta tilde and $\tilde{\Delta}_{ASH}$ specifies the corrected delta.

After SH, cointegration tests are frequently utilized to examine whether a linear long run association between the stationary variables exists. This cointegration test for error-correction models looks into the possibility that there is no cointegration. In equation 6, the test equation is equated as follows:

$$\Delta y_{it} = \chi_i' d_t + \varphi_i y_{it-1} + \lambda_i' x_{it-1} + \sum_{j=1}^{pi} \omega_{ij} \Delta y_{it-j} + \sum_{j=1}^{pi} \eta_{ij} \Delta x_{it-j} + \quad (6)$$

In above equation (6), ω_{ij} is the error correction parameter, $\chi_t = (\chi_{i1}, \chi_{i2})'$ indicates vector of parameters, $d_t = (1, t)'$ represents deterministic components. This equation produces panel means tests (P_t and P_a) and group mean tests (G_t and G_a). More advanced estimators address issues such as slope heterogeneity, CD, and dynamics. After addressing these issues, the fully modified OLS (FMOLS) and dynamic OLS (DOLS) estimators provide long-run estimates for cointegrated relationships. These techniques yield unbiased estimates and help overcome endogeneity concerns.

Conventional FMOLS estimators are indicated by β^*_{FMOLS}. At the same time, the t-statistics allied with estimators of FMOLS which are given below:

$$t\beta^{*FMOLS} = N^{-1/2} / \sum_{i=1}^{N} t_{\beta FMOLS,I} \quad (7)$$

After this, the equation of FMOLS to overcome the issues of serial correlation and biased endogeneity is equated below:

$$\beta_i^* = (\acute{X}_i X_i)^{-1} (\acute{X}_i y_i^* - T\delta) \quad (8)$$

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Further, the following is the FMOLS equation for long-term estimation:

$$\beta FMOLS = [\frac{1}{N}\sum_{i=1}^{N}(\sum_{t=1}^{T}(Ait - barAi))^2]^{-1} \times \sum_{t=1}^{T}(Ait - barAi)^2)\, barYit - Tbar\Delta e\mu$$

(9)

After equated FMOLS, the DOLS equation is given below as follows:

$$t_{\beta^*DOLS} = N^{-1/2}\sum_{i=1}^{N} t_{\beta DOLS,I}$$

(10)

Additionally, the following is the DOLS equation for long-term estimation:

$$\beta DOLS = [\frac{1}{N}\sum_{i=1}^{N}(\sum_{t-1}^{T}(AitA'it))^2]^{-1}\sum_{i=1}^{N}(\sum_{t-1}^{T}(AitYit)]$$

(11)

The above equations of FMOLS and DOLS (7 to 11) are equated to estimate the long run effect of technological innovation (TEI), digitalization (DIGI), clean energy as renewable energy (REN), economic growth (ECR), and total resource rents (TRR) on environmental sustainability (ENS) in South Asia.

4. Findings and Discussions

This section presents the analysis of the effects of technological innovation (TEI), digitalization (DIGI), economic growth (ECR), clean energy (REN), and total resource rents (TRR) on environmental sustainability (ENS) in South Asian economies. For this purpose, the estimates of different econometric techniques are given as follows:

4.1 Descriptive statistics

This section presents descriptive statistics for the variables, including mean, standard deviation, skewness, kurtosis, and the Jarque-Bera test. Technological innovation (TEI), digitalization (DIGI), economic growth (ECR), clean energy as renewable energy (REN), and total resource rents (TRR) are defined statistically in relation to environmental sustainability (ENS). Table 2 presents the statistics, and the means show that the average score for ENS was 9.485; for TEI, 4.881; DIGI, 1.099; ECR, 24.273; REN, 3.739; and TRR, -0.554. With regard to dispersion, DIGI exhibited the greatest variability as indicated by its high standard deviation (SD = 3.754); TEI was second (SD = 2.861); ENS third (SD = 2.699); and REN showed the least amount of variability with the lowest SD of .265. ENS, TEI, and ECR showed positive skewness, while DIGI, REN, and TRR showed negative skewness; TRR had the strongest negative skewness (-1.244). Kurtosis ranged from 2.008 for ECR to 3.431 for TRR, indicating that most of these variables' distributions were somewhat leptokurtic (peaked), while TRR's distribution was even more so. All JB-probabilities were statistically significant at the 1% level, allowing us to reject the null hypotheses of normality for each variable. These descriptive statistics reveal substantial variability across our panel data variables in South Asia and provide a solid foundation for further analysis.

Table 2: Descriptive Statistics

South Asian Countries						
Variables	**ENS**	**TEI**	**DIGI**	**ECR**	**REN**	**TRR**
Mean	9.485	4.881	1.099	24.273	3.739	-0.554
Std. Dev.	2.699	2.861	3.754	2.333	0.265	2.074

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Skewness	0.242	0.362	-0.680	-0.111	-0.554	-1.244
Kurtosis	2.057	2.197	2.181	2.008	2.547	3.431
Jarque-Bera	10.482	10.921	23.529	9.645	13.391	59.518
Probability	0.005	0.004	0.000	0.008	0.001	0.000

4.2 Correlation Analysis

A correlation coefficient examines the extent of correlation between variables. The correlation matrix for the variables of environmental sustainability (ENS), technological innovation (TEI), digitalization (DIGI), economic growth (ECR), renewable energy (REN), and total resource rents (TRR) for the selected South Asia countries is provided in Table 3. As shown in the correlation matrix, ENS is inversely associated with both TEI (-0.749) and REN (-0.672); this implies that as technological innovation and renewable energy increase, carbon dioxide emissions decrease. On the other hand, ENS is positively related to ECR (0.782) and TRR (0.403); thus, higher economic growth and resource rents are associated with greater environmental pressure; however, it is inversely related to DIGI (-0.325). Of the independent variables, TEI is positively related to both ECR (0.733) and REN (0.701); DIGI is positively related to both REN (0.638) and TRR (0.389); additionally, DIGI is positively related to ECR (0.175). Finally, there exists a positive relationship between ECR and REN (0.422); however, the relationship between ECR and TRR is weakly positive (0.133). Therefore, based on the correlation coefficients among the independent variables, they appear sufficiently distinct to avoid serious multicollinearity concerns in the subsequent econometric analysis.

Table 3: Correlation Matrix

South Asian Countries						
Correlation	**ENS**	**TEI**	**DIGI**	**ECR**	**REN**	**TRR**
ENS	1.000					
TEI	-0.749	1.000				
DIGI	-0.325	0.105	1.000			
ECR	0.782	0.733	0.175	1.000		
REN	-0.672	0.701	0.638	0.422	1.000	
TRR	0.403	0.337	0.389	0.133	0.143	1.000

4.3 Cross-Dependence Test

In the panel data analysis, checking the CD of variables first is imperative. The results of Table 4 on cross-section dependence (CD) tests for the selected South Asian countries indicate there is a significant cross-section dependency for all the examined variables, including Environmental Sustainability (ENS), Technological Innovation (TEI), Digitalization (DIGI), Economic Growth (ECR), Renewable Energy (REN), and Total Resource Rent (TRR). The calculated cross-section dependency statistic for ENS is 22.175, for TEI is

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16.662, for DIGI is 20.016, for ECR is 22.974, for REN is 19.008, and for TRR is 45.87. All have an estimated p-value of .000, rejecting the null hypothesis of independence for all variables at the 1 percent significance level. These findings suggest that developments in one South Asian economy will likely affect the development of another, possibly through regional economic integration or shared environmental conditions, shared technological innovations, energy market linkages, or resource-related interactions. Therefore, it is important to use econometric methodologies that account for cross-country dependencies among countries when conducting analysis of these data sets rather than assume complete independence of each country's observations.

Table 4: Cross-Sectional Dependence (CD) Test

South Asian Countries		
Variables	**CD Test**	**Prob.**
ENS	22.175***	0.000
TEI	16.662***	0.000
DIGI	20.016***	0.000
ECR	22.974***	0.000
REN	19.008***	0.000
TRR	45.870***	0.000

Note: Level of Significance ***1%, **5%, *10%

4.4 Slope Homogeneity

After the CD test, it is crucial to test the slope homogeneity (SH). Table 5 presents the slope homogeneity estimates. The results show that the Δ Test and Adj Δ Test values (8.621 and 9.119) are statistically significant at the 1 percent level, meaning the null hypothesis of "no slope heterogeneity" is rejected. Therefore, the model shows slope heterogeneity in the South Asian region economies.

Table 5: Slope Homogeneity Test

South Asian Countries		
Test	**Estimate**	**Prob.**
Δ Test	8.621***	0.000
Adj Δ Test	9.119***	0.000

Note: Level of Significance ***1%, **5%, *10%

4.5 Panel Cointegration Test

The panel cointegration test estimates the long-run relationship between the variables. The cointegration test tests the null hypothesis that no cointegration exists, while the alternative hypothesis suggests that the dependent variable coexists over time with the explanatory variables. Table 6 presents the panel cointegration test estimates for the South Asian region. The outcomes indicate that all tests G_t, G_a, P_t, and P_a have statistically significant values, suggesting long-run cointegration among technological innovation (TEI), digitalization (DIGI), economic growth (ECR), clean energy (REN), total resource

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rents (TRR), and environmental sustainability (ENS) in South Asian economies.

Table 6: Westerlund Cointegration Test

South Asian Countries			
Statistics	**Value**	**Z-value**	**P-value**
G_t	-2.997**	-2.279	0.013
G_a	-3.433***	-5.244	0.000
P_t	-3.182***	-4.493	0.001
P_a	-6.629***	-4.864	0.000

Note: Level of Significance ***1%, **5%, *10%

4.6 FMOLS and DOLS Analysis in South Asian Countries

The evidence in Table 7 on the determinants of environmental sustainability in selected South Asian economies is consistent across both FMOLS and DOLS results. As shown by the coefficients of -0.208 and -0.226, both statistically significant at the 1% confidence level, an increase in technological innovation decreases CO_2 emissions. Therefore, technological innovation improves environmental sustainability by reducing emissions. Potential reasons include increased production efficiency, lower energy intensity, cleaner production processes, and the use of new, low-carbon technologies. These results align with those of Yu et al. (2023), which indicate that technological factors were among the most important contributors to emissions reduction in South Asian economies. Farooq et al. (2024) show that green technological innovation can reduce CO_2 emissions in several South Asian countries. This result also supports theoretical predictions by Acemoglu et al. (2012), who argued that technological change can lead to cleaner production processes, and Popp (2002), who showed that innovation can stimulate the development of energy-saving technologies. The literature also supports the environmental benefits of technological innovation in other Asian economies (Zhang et al., 2026). Therefore, these findings suggest that increases in technology contribute positively to environmental improvements across all sampled economies. Digitalization (DIGI) has an important adverse effect on CO_2 emissions. Both coefficients are negative (-0.115 for FMOLS and -0.049 for DOLS). These negative coefficients show how digitalization improves environmental sustainability. Digitalization may reduce emissions by improving resource allocation, production efficiency, energy management, transportation systems, and data exchange. Murshed (2024) found similar results to our findings that digitalization contributes to reduced carbon-emission growth in South Asia. Similarly, Feroz et al. (2021) reported that digital transformation enables improved environmental performance through increased resource efficiency, and Charfeddine & Umlai (2023) identified substantial evidence supporting environmentally favorable impacts associated with digitalization. Kopp et al. (2023) showed that digitalization produces environmental benefits through efficiency gains. Recent studies in South Asia show that digitalization can deliver environmental benefits that support sustainability, alongside links to renewable energy and appropriate governance structures (Imran et al., 2026). Therefore, because the DIGI coefficient values were negative, they indicate that digital transformation generates

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greater environmental benefits than the emissions it may produce across all sample countries. Renewable Energy (REN) is negatively correlated with carbon dioxide (CO_2) emissions at statistically significant levels based on FMOLS & DOLS; using regression coefficients of -0.099 and -0.104, respectively. Therefore, increased use of renewable energy will promote environmental sustainability by reducing emissions. The primary economic mechanism for reducing pollution from energy consumption is replacing fossil fuel-derived energy with cleaner alternatives, i.e., solar, wind, and hydro power. Additionally, this research supports prior studies by Batool et al. (2022), which found that renewable energy improves environmental quality in developing countries in Eastern and Southern Asia. Similarly, Zeb et al. (2014) identified renewable energy as one of the most influential factors shaping the environmental development relationship among five South Asian countries: Bangladesh, India, Nepal, Pakistan, and Sri Lanka. In addition to the aforementioned study, Jiang et al. (2022) demonstrated that renewable energy generates substantial environmental impacts. Furthermore, Balsalobre-Lorente et al. (2018) showed that renewable electricity production can improve environmental conditions. Overall, the consistently negative values associated with the REN coefficient indicate that renewable energy growth will effectively decrease carbon dioxide emissions in South Asia. Compared with environmental sustainability, economic growth (ECR) positively and significantly affects CO_2 emissions, as shown by both the FMOLS coefficient (0.248) and the DOLS coefficient (0.276). Economic growth causes a negative impact on environmental sustainability through an increase in CO_2 emissions. This reflects a "scale" effect from increased industrial production, industrialization, transportation, and energy consumption driven by growth dependent on carbon-based energy sources. This result is similar to those reported in Yu et al. (2023) and Farooq et al. (2024), which identified economic development as a source of increased emissions in South Asian countries. Furthermore, Balsalobre-Lorente et al. (2018) found economic growth to be one of the primary factors contributing to CO_2 emissions but noted that renewable energy can reduce or eliminate this pressure. Therefore, the findings suggest that the sampled economies are still far from achieving full decoupling of economic growth from environmental degradation. Finally, the overall coefficient for Total Resource Rent (TRR) has a positive and statistically significant relationship to carbon dioxide (CO_2) emissions, with values of 0.173 and 0.138 using FMOLS and DOLS, respectively. Thus, higher dependency on resources generally reduces environmental sustainability by increasing energy consumption for extraction, processing, and transport, as well as pollution from production processes. These results align with Huang et al. (2020), who highlighted the economic implications of resource extraction in developing Asian economies, and Huang et al. (2023), who found that natural resource rent was linked to reduced environmental quality. Likewise, Wang et al. (2024) also identified high levels of resource dependency as an important factor in environmental concerns in South Asia. In general, innovations such as technology, digitalization, and renewable energy reduce CO_2 emissions, while economic growth and resource rents increase them. Because the sign is uniform for the same variables in both estimators, we conclude that the long-run relations are stable. While the significance levels for DIGI and TRR are slightly stronger for FMOLS, the absolute values of the coefficients for TEI and REN are slightly larger for DOLS. Hence, FMOLS may be our primary estimator and DOLS a robustness check, and agreement between these two methodologies will strengthen confidence in our conclusions.

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Table 7: FMOLS and DOLS Long-run Estimates

South Asian Countries				
Variables	**FMOLS**		**DOLS**	
	Coefficients	**Std. Error**	**Coefficients**	**Std. Error**
TEI	-0.208***	0.031	-0.226***	0.040
DIGI	-0.115***	0.027	-0.049**	0.023
ECR	0.248***	0.057	0.276***	0.071
REN	-0.099***	0.014	-0.104***	0.029
TRR	0.173***	0.058	0.138**	0.065

Note: Level of Significance ***1%, **5%, *10%

5. Conclusion and Recommendations

This study examines how key factors (technological innovation, digitalization, renewable energy, economic growth, and total resource rents) affect long-term environmental sustainability in South Asian countries. To find out if there is a long-term relationship between these variables, an econometric model was developed to test this hypothesis. The model produced statistically significant coefficients for most independent variables and consistent signs across all of them, adding confidence to the results. Additionally, it found that technological innovation, digitalization, and renewable energy support environmental sustainability and reduce CO_2 emissions. However, economic growth and total resource rents both have a positive relationship with CO_2 emissions, which hurts environmental sustainability and increases environmental pressures. Thus, this study demonstrates that environmental sustainability in South Asia is dependent upon the technological and energy structures used, in addition to economic expansion.

Therefore, the results provide evidence that technological innovations have a negative and significant impact on CO_2 emissions. Therefore, technology advances can be beneficial toward producing cleaner and more efficient products. As such, developing countries in South Asia should implement stronger incentives for research and development focused on sustainable environments, develop more efficient green technologies, and develop more innovative low-carbon production processes. Also, increased financial investment in green patents and clean-technology initiatives is needed to better leverage the benefits of technological advances. Governments can promote digital transformation in energy management, transportation, manufacturing, and public service delivery by investing in smart grids, digital monitoring systems, intelligent transportation systems, and other digital resource-management platforms.

Renewable energy is an additional key path to achieving environmental sustainability. The negative and statistically significant coefficient for renewable energy indicates that CO_2 emissions decrease as the proportion of renewable energy increases. To this end, South Asian governments should promote the development of Solar, Wind, Hydropower, and other low-carbon energy sources, and reduce their reliance on carbon-intensive energy. To do this, these Governments will need to continue investing in renewable-energy Infrastructure, improve electricity-grid capacity, offer financial incentives for clean-energy projects, and implement policies that support

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private-sector participation in renewable-energy development. Furthermore, renewable energy development should be integrated into technological and digital transformation to meet rising electricity demand from industrialization and digitalization through cleaner energy sources. Rather than negatively affecting carbon dioxide (CO_2) emissions, economic growth has a positive and significant influence, indicating that economic growth remains associated with environmental pressure in the sampled countries. This finding suggests policy should focus on changing the underlying structure of how economies operate rather than restricting economic development. Governments can encourage green industrialization, energy efficiency, clean transportation systems, and less energy-intensive manufacturing processes so that economic growth becomes decoupled from carbon emissions. Similarly, total resource rents have a positive effect, meaning resource-based economic activities contribute to environmental problems. Therefore, resource-rich countries must improve regulations for all aspects of extraction, processing, and transportation activities that adversely affect the environment; they must also improve monitoring of resource-intensive industries. Resource revenue may also be directed toward renewable energy sources, green infrastructure, environmental technologies, and economic diversification, but not to support or continue resource-dependent economic activity.

Overall, South Asian countries have many options to improve their environment through technological innovation, digitalization, and expanding renewable energy sources, alongside a gradual shift toward clean, diverse economies. In addition, traditional economic growth models carry higher environmental costs and resource dependency, which will require additional regulatory investment frameworks. The similarity between the FMOLS & DOLS results supports the validity of the long-run relationship and provides a strong empirical foundation for these policy recommendations.

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