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Research article

Charting the path to sustainable prosperity: Harnessing innovation, renewable energy, and institutional excellence for a greener tomorrow

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ABSTRACT

Climate change and global warming have led to significant economic challenges in the recent past. Currently, the economic growth strategy prevailing in the region is ineffective, which adversely affects the environment of the South Asian region through the unprecedented increase in CO_2 emissions. The present study focuses on investigating the impact of technological advancements, renewable energy resources, and the strength of institutional quality on carbon emissions. Furthermore, the study focused on challenges faced in promoting renewable energy as well as governmental policies to encourage the adoption and promotion of renewable energy. We have targeted South Asian economies (Pakistan, India, Nepal, Bangladesh, and Sri Lanka) and employed a quantitative research design using data from 1990 to 2022 and employing a Random and fixed effect model. We found that technological innovation and environmental quality play a significant role in sustainability in the South Asian region. We have also applied a sensitivity analysis which shows that data are reliable and stable. In order to ensure economic growth without causing environmental destruction policymakers must prioritize the implementation and development of renewable energy sources through state-level policies. Furthermore, this could entail responsible acts like reforestation a decrease in deforestation, and the promotion of sustainable and effective practices.

1. Introduction

Climate change and global warming have led to significant economic challenges in the recent past [1]. One of the major causes of climate change is greenhouse emissions while CO_2 (corban dioxide) is the major component of greenhouse gases being identified [2]. According to the International Energy Agency (IEA) report 2021 increased uses of fossil fuels have led to higher levels of CO_2 emissions which calls for prudent actions to mitigate or reduce these emissions and achieve suitable development goals (SDGs).

To address these climate issues of global warming and environmental challenges, the 27th Conference of Parties (COP-27) was held at Sharm EI Sheikh (Egypt) Intergovernmental Panel on Climate Change (IPCC) was established. Before this event, the Paris Agreement (COP-21) also had great significance in these Summit meetings. The main agendas of these summits are to bring collective efforts to

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reduce global temperature up to 2 °C and to encourage further efforts to minimize environmental damages [3–6]. To protect the world's planet and ensure human survival, aggressive climate changes require prudent, strong, and immediate actions. The focus of the Sharm EI Sheikh conference (COP-27) was both mitigation and adaptation policies. The particular emphasis is on reducing non-renewable energy, the world leader recognized its significant contribution to global emissions. As a result, many economies of the world tried to reduce CO_2 emissions, Development of environmentally friendly technologies plays a crucial role in the transformation of many economic systems [7–9]. Hussain et al. [10], tested the Environmental Kuznets curve in the top polluted economies of the world. They found that the Environmental Kuznets curve exists in these economies.

A recent Technological advancement, known as cleaner technological innovations, aims to reduce energy consumption, lower pollution emissions, restore ecological balance, and contribute to a green future [11–14]. Most of the emerging economies of the globe are focusing on green tech growth and extraction of renewable energy sources to Combat environmental issues [15–18]. According to Wang et al. [19], and Lin & Ma [20], investment in green tech innovation can boost economic activity, enhance production and provide a prudent solution to mitigate the CO_2 emission. In addition, technological advancement has a significant impact on various aspects of human life, including the environment. Over the past few years, South Asian economies have experienced rapid growth in industrialization, high population, and Gross domestic product (GDP) which significantly affected the environmental quality of that region. Studies have found that high population growth, deforestation, air pollution, and urbanization affect the environment negatively [21–23].

South Asian economies also focus on investing in green technological projects to tackle environmental challenges. Focusing on the improvement of renewable energy sources and improving waste management systems can help decline GHG emissions. In addition, in the development of the Green-tech innovation reduction of CO_2 emissions and improvement in environmental quality, and institutions can play a crucial role in encouraging environmental protection initiatives [24–26]. Most of the nations are actively participating in implementing a robust institutional framework to Combat Corruption, strengthen financial oversight, and improve environmental conditions and technologies [27–30]. Du et al. [31], argued that the ability of a country to tackle environmental issues lies in the strength of its institutional capabilities. Research to deal with environmental challenges is an active field of research [32–35]. Reduction of CO_2 emissions requires more effective institutions have been recommended by many researchers [36–39].

Although there is limited research on the impact and implications on the environment, it is a fact that quality institutions have a positive role, particularly in terms of mitigating crimes and Corruption in developing nations. Therefore, the purpose of this study is to examine the influence of green tech innovation and the quality of institutions on CO_2 emission in South Asian nations. The reasons behind South Asia are several [40–43]. Firstly, the vulnerability of the South Asian region to the severe consequences of Climate change, can be reduced by promoting green economic growth. It is projected that the region will Warm up to 2–6 °C by the end of the 21st century [44–47].

Currently, the economic growth strategy prevailing in this region is ineffective, which adversely affects the environment of the South Asian region through the unprecedented increase in CO_2 emissions. This surge is primarily driven by accelerating demand for energy resulting from rapid economic growth leading to a rise in the level of greenhouse gases and pollutants [48–51]. The escalating CO_2 emissions contribute to global warming which further deteriorates The Environmental Challenges. Additionally, a major portion of the South Asian population is trapped in a vicious circle of poverty, the region must pursue sustainable growth without compromising its economic development. Analyzing the pattern of CO_2 emission in the region offers valuable insights into fostering a green economy that promotes economic growth while ensuring environmental Sustainability.

The South Asian region holds significant potential in terms of renewable energy and natural resources which are crucial for sustainable development. Renewable energy resources e-i., solar energy, wind energy, and hydro-power are widely distributed in this region. However, rapid industrialization and GDP growth have resulted in reducing natural and energy resources, which leads to ecological problems. To tackle these challenges, these economies are investing in renewable energy resources to reduce their dependency on fossil fuels i.e., oil, gas, and coal which are the main agents of CO_2 emission [52].

This study focuses on examining the impact of technological advancements, renewable energy resources, and the strength of institutional quality. This study further focused on obstacles faced in promoting renewable energy as well as governmental policies to encourage the adoption and promotion of renewable energy. Furthermore, this study aims to explore the strategies adopted by the South Asian region and the practices applied to the other regions facing similar environmental challenges. Pakistan possesses a variety of renewable energy resources i-e wind and solar while India has the largest resources in South Asia followed by Sri Lanka and Pakistan. However, as the living standard increases during the last stage of GDP growth, most countries hesitate to consider the need for renewable energy, accessibility, energy saving, and other environmental solutions [53,54]. The most challenging threat, which is faced by the residents of this region is Changing global climatic patterns and it is evident that the emission of CO_2 into the atmosphere is one of the major causes of depletion of renewable resources. Therefore, the findings of this study will be very valuable for researchers, policymakers, and stakeholders involved in environmental management and achieving sustainable development goals in South Asia.

This study provides a significant contribution to the existing literature on policy-making issues in South Asia by proposing a design of Sustainable development Strategies. Current policies of the region lack in adoption of sustainable technologies, that Can reduce wastage of energy consumption and promote efficiency in the region. Now there is a dire need for state-level policies to prioritize the implementation and development of renewable sources of energy to ensure economic growth without environmental destruction. These Strategies should also focus on promoting forest management practices which promote a balance between economic growth and environmental Conservation. Policymakers should give top priority to the conservation and efficient utilization of natural resources i-e water, land, and minerals, and sustainable consumption of these resources. Additionally, this may involve prudent actions such as Afforestation, reduction in deforestation, and promotion of Sustainable and efficient practices.

The remaining paper contains the following sections. Literature review in section 2, section 3 contains data and methodology, section 4 contains econometric procedure, section 5 contains data, section 6 contains estimation, section 7 contains robustness, and section 8 contains conclusion and policy implications.

2. Literature review

Studies on sustainable development and its impact have received significant attention in recent years. Existing literature gives a rich archival record in this regard. Keeping our research objectives under consideration, we have accumulated a summary of existing research across our major themes i.e., Technological Innovation, institutional excellence, and its impact on the environment. It provides a glimpse of the existing body of knowledge on the selected areas and helps us to identify potential research gaps.

A technological innovation (TI) is frequently as recognized the most effective source of achieving sustainable growth objectives [19]. Nosheen et al. [55], investigated the transformative role of renewable energy in shaping economic landscapes selecting the top 20 high-energy consumption economies and using data from 1990 to 2021. These results demonstrate the critical role that renewable energy plays in determining steady GDP growth and suggest that these nations are headed toward sustainable Development. The study implications for policy include a call for cooperation between governments international organizations and energy planners. In this context, high-tech developments are likely to have an impact on environmental issues. It reduces environmental expenditures while also recovering resource extraction costs. Several research studies on the growth of technology & its ecological impact have lately emerged, with varying results. Previous research utilized CO_2 production as a proxy for environmental degradation to predict the relationship between technological developments and the destruction of the environment. Zhang et al. [56], for instance, analyzed provincial data from China to study the association between ecological contamination and innovation in technology spanning 2000 to 2010, employing the Stochastic Implications by Regression on Population, Affluence, & Technology (STIRPAT) model paradigm. The panel technique's projected evidence reveals that technological developments helped to reduce pollution levels over time. The concept of green growth, introduced by the United Nations in 2005, proposes achieving sustainable economic development while minimizing environmental damage [57]. Green Growth, emphasizing environmental harmony through the efficient use of natural resources, advocates for national Development and Growth [58]. Organizations striving for performance excellence and sustained positive effects on people and the environment heavily rely on technology [59]. Choudhury et al., investigated the impact of the top five most polluted economies in the world are examined in this study in relation to their economic growth and carbon emissions [1]. The research employs a Panel Autoregressive Distributed Lag (PARDL) technique to obtain an estimate on an empirical level. The system moves toward a long-run equilibrium following a shock because the estimated results indicate that the ECM value is significant and negative. Research demonstrates that in the short and long terms GDP and energy consumption are positively and significantly correlated with CO2 emissions. Additionally the top five most polluted countries GDP2 effect shows the Kuznets curve (EKC) effect. Policymakers acknowledge the potential environmental repercussions of technological advancements and advocate for a shift towards environmentally friendly or clean technologies to mitigate ecological catastrophes [60]. Green innovation, encompassing technological, product, process, and management innovation, is crucial in protecting environmental interests [61]. Adebayo et al. employed a CS-ARDL modeling approach to assess the negative impact of technical innovations, natural resources, & clean energy sources on CO_2 emissions in the countries of the BRICS group from 1990 to 2019 [62]. Also, the coupling of technology improvements with clean energy sources and natural assets helps to reduce harmful emissions. The OECD Investigated twenty-nine countries from 19999 to 2014 [63]. They employed the GMM techniques to estimate the data. This study found that eco-friendly patents and technological advances had a diminishing impact on regional environmental contamination. Green industrial policies, including industry promotion, subsidies, job creation, tax credits, & market formation, are critical in encouraging domestic green Growth [64]. These policies impact how technologies attain market dominance, with possible conflicts occurring at the crossroads of local and foreign policy aims. When well specified, green industrial strategies have the potential to encourage green development by harmonizing with National Innovation Systems and global market demands [65]. Policy judgment timeframe, architecture, and constancy can all influence lead marketplaces. It highlights the value of information capabilities and national modernization schemes in the development of innovation. Akbar et al. [66] reported the impact of renewable and non-renewable energy consumption on the environment using data from 1971 to 2022. The findings show that a comparison of the effects of renewable and non-renewable energy consumption on carbon dioxide emissions shows that while non-renewable energy consumption raises CO_2 emissions renewable energy consumption lowers them according to research. While secondary education improves environmental quality by reducing CO_2 urbanization globalization primary education and economic growth all increase carbon emissions. Furthermore, Wei et al. investigated the influence of high-tech developments, green power, and financial growth on Brazil's environmental trajectory from 1990 to 2018 [67]. The results of the dynamic Auto Regressive Distributed Lag model revealed that renewable energy, technical advancements, & globalization lower the environmental trajectory, however, economic expansion exacerbates the environment.

Renewable and alternative sources of energy are both environmentally friendly. They have been identified as a source of lower pollution concentrations, hence minimizing ecological impact. Most works reflect the reducing impact of renewable and substitute resources on the ecological imbalance. The convergence of green growth and sustainable development policies with environmental and climate policies is critical for developing countries to achieve broad policy goals [68]. This integration includes policies linked to R&D, innovation, and green industry. Green Growth is supported by evolutionary economic principles such as lead markets, innovation induction by policy, first-mover advantages, and policy-established nations, leapfrogging, & catch-up [69]. The Porter Hypothesis (PH) contends that well-designed environmental restrictions can stimulate rather than stifle domestic economic Growth [70]. It refutes the notion that ecological laws inevitably hamper economic advancement and argues that they can boost competitiveness. The PH, based on evolutionary economics, considers innovation, research, Development (R&D), and technological advancement dynamic processes impacted by various factors. Jaffe and Palmer present weak to narrowly strong interpretations, each highlighting a particular component of the link between environmental restrictions and innovation [71].

Adebayo and Kirikkaleli also established the correlation between renewable resources & carbon dioxide radiation utilizing the FMOLS method in a worldwide framework [72]. This study found that increasing the consumption of renewable resources helps to reduce the detrimental effects of greenhouse gases on the planet. Similarly, Shang et al. investigated the dynamic influence of green & renewable energy resources on the environment, & their findings demonstrated that increasing renewable energy reduces environmental footprint levels [73]. An equivalent assessment was conducted by Usman and Radulescu [74], for the greatest nuclear energy-producing countries utilizing a set of data from the period 1990 to 2019. The study found that the rise in nuclear & renewable energy resources reduces environmental degradation.

The broad scope of the previous investigations resulted in the absence of several important areas of knowledge. Thus, the current work focuses on correcting these issues and shortcomings in our computations. First and foremost, no research has been conducted to investigate and expound on the relationship between institutional quality, renewable energy use, FDI, and technological innovation in South Asian countries.

Furthermore, past studies have produced contradictory results about the relationships between these parameters. Similarly, numerous past research works have focused on regulating the root reasons for increasing environmental excellence in South Asian economies. Furthermore, no examination has been conducted into the comprehensive effects & joint effects of these planned factors in this alliance. South Asian countries have freshly faced greater environmentally friendly challenges; as an outcome, effective actions ought to be implemented and promoted to improve matters. In this esteem, the current study may assist the administrations, organizations, policymakers, & governments of these nations in pursuing further appropriate, applied, and practical efforts related to environmental defense in general, & particularly in the instance of these countries.

3. Materials and methods

To investigate the influence of technological innovation on green growth within the Southeast Asian economy, we put forth a linear regression model. The response variable in our analysis is GG, which represents Green Growth for country i at time t. The independent variable of significance is TI, which stands for Technological Innovation for the same country and period. Following [75] and many other studies, we use the following model:

3.1. Model

$$LnCo2_{it} = \beta_0 + \beta_1 lnTECH_{it} + \beta_2 \ln GDP_{it} + \beta_3 lnRD_{it} + \beta_4 lnFDI_{it} + \beta_5 lnER_{it} + \beta_6 lnREW_{it} + \beta_7 lnIQ_{it} + \beta_8 lnPOP_{it} + \alpha_i + \varepsilon_{it}$$

Green Growth in Country i at time t is abbreviated as $\mathbf{CO_2}$ it. We are most interested in technological innovation for the country i at time t, which the symbol TECH abbreviates. **GDP**it signifies a nation's Gross Domestic Product (GDP) at time t. **RD**it is a research and development investment for country i at time t. **FDI**it is an abbreviation for f i at time t **ER**it denotes the environmental regulations for country i during Time t. **REW**it is an acronym for Renewable Energy in Country i at time t. **IQ**it is an acronym for Institutional Quality in station i at time t. The population density of nation i at time t is denoted by **POP**it.

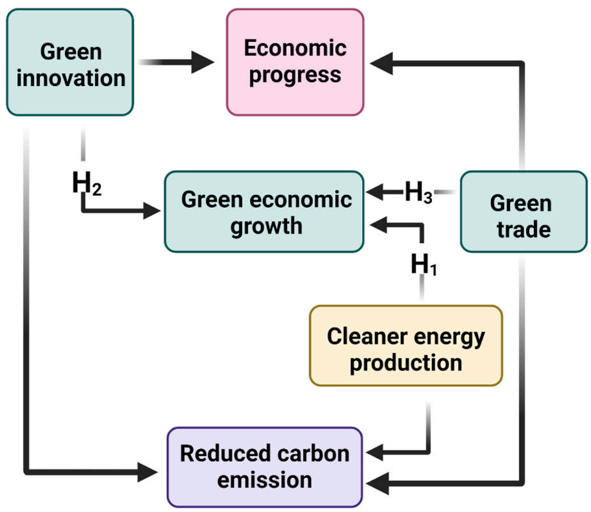

Fig. 1. The flow chart of the present research.

3.2. Methodological flowchart

The methodological flowchart of the current study is shown in Fig. 1 below:

3.3. Justification of variables

3.3.1. Economic growth

An increase in Gross Domestic Product (GDP) signifies a surge in economic activity and affluence. A more robust economic base facilitates allocations towards environmentally friendly infrastructure, technologies, and initiatives when considering sustainable growth. Liousse et al. [76] and Twerefou et al. [77] found that nations can boost their GDP by allocating their resources efficiently to environmentally friendly projects, policies, and Research & Development. It indicates the prosperity of a country and is positive news for businesses and workers.

3.3.2. Technological advancement

Technology innovation is the major driver of economic prosperity and competitiveness. Technology use can handle the climate issues and it help in launch green project which can enhanced environmental sustainability [78]. It plays a key role in the promotion of sustainable development. Solar panels and wind farms generate a massive amount of renewable energy that increases the efficiency of the environment and makes green construction possible. Widespread digitalization also means that more people can work from home and reduce personal emissions. Solar energy, bio-fuels, wastewater treatment, wave, and tidal energy, and eco vehicles all contribute to the environmental sustainability agenda.

3.3.3. Research and development

The first step to allocating Research & Development is to align them with your organization's strategy and vision. It can lead to innovations in your business. Spending on Research & Development also plays a key role in environmental sustainability. Through technology, we can create innovative solutions that benefit the environment and society, drive growth, and support economic vitality. By creating new markets and employment opportunities, organizations that place a premium on R&D in green technologies establish themselves as leaders in sustainability, thereby bolstering their environmental credentials and contributing to economic expansion [79].

3.3.4. Environmental regulations

Environmental governance is critical in establishing a sustainable framework, so stringent ecological regulations are indispensable. They facilitate the implementation of environmentally sustainable measures, regulate pollution, and establish benchmarks for ethical business conduct. Although there may be initial difficulties in adhering to environmental regulations, they establish a fair and balanced environment that encourages innovation and compels companies to bear the financial burdens of ecological damage; thus, they contribute to the long-term viability of the economy [80].

3.3.5. Renewable energy

Investing in renewable energy is a worldwide necessity to shift towards an economy with reduced carbon emissions. Sustainable alternatives to conventional, environmentally detrimental energy sources are renewable sources. In addition to its positive environmental impacts, investments in renewable energy contribute to expanding the renewable energy sector, bolster energy security, and mitigate reliance on volatile fossil fuel markets [81].

3.3.6. Institutional quality

Institutional integrity is critical for enforcing environmental policies, establishing legal frameworks that promote sustainable practices, and maintaining a stable business environment. High institutional quality fosters sustainable investments through the establishment of a regulatory environment that is both transparent and predictable. Organizations flourish in settings that uphold the rule of law, which mitigates the uncertainties and risks linked to unsustainable practices [82].

3.3.7. Population density

The issue of population density presents sustainable development with a range of obstacles and prospects. The imperative to accommodate densely populated areas motivates advancements in resource efficiency, ultimately resulting in the implementation of ecologically sustainable technologies. In densely populated regions, sustainable technologies prioritizing resource efficiency become indispensable [83].

4. Econometric procedure

When employing the estimation method with panel data, involving random and fixed effects models, a systematic succession of procedures is required to provide reliable and understandable findings. After specifying and structuring the model for the panel data set, the estimation stage starts by choosing to treat entity-specific fixed effects as random variables (RV) or adopting them. The hypothesis of random effects asserts that effects are specific for every entity and not connected to the independent variables or explanatory variables, however, the fixed effects model includes qualities that are stable throughout time. The general form of the panel model:

$$Y_{it} = \alpha_{yxt} Z_{it} + \beta_{yzt} X_i + \gamma_t \tau_i + \mu_{it}$$

In the above equation Y_{it} indicating the dependent variable for entity i at time t, while the independent variable Z for entity i at time t, and X for entity i at time t, γ_t indecatinghe time specific effect, τ_i indecating the entity specific effect and μ is the error term.

Model Variations:

1. Time-invariant γ: $\gamma_t = 1$ f for all t
2. Time-invariant γ and α_{yxt}: $\gamma_t = 1$, $\beta_{yzt} = \beta_{yz}$ for all t
3. Time-invariant γ, β_{yx} , and β_{yz}: $\gamma_t = 1$, $\beta_{yxt} = \beta_{yx}$, $\beta_{yzt} = \beta_{yz}$ for all t
4. Time-invariant γ, α_{yx} , β_{yz} , and COV(xit, τ_i) = 0: $\gamma_t = 1$, = , = ,COV(.) = 0 for all $\gamma_t = 1$, $\alpha_{yxt} = \alpha_{yx}$, $\beta_{yzt} = \beta_{yz}$,COV(xit, τ_i) =) = 0 for all t
5. (a) Fail to reject (4) - Time-invariant γ, α_{yx} , β_{yz} , COV(xit, τ_i) = 0, $\sigma\epsilon$: $\gamma_t = 1$, $\alpha_{yxt} = \alpha_{yx}$, $\beta_{yzt} = \beta_{yz}$, COV(xit, τ_i) = 0, $\sigma\epsilon t = \sigma\epsilon$ for all t

5 (b) Reject (4) - Time-invariant γ, βyx, βyz, $\sigma\epsilon$: $\gamma_t = 1$, $\alpha_{yxt} = \alpha_{yx}$, $\beta_{yzt} = \beta_{yz}$, $\sigma\epsilon t = \sigma\epsilon$ for all t

6. Classic Random Effects Model (REM) - Equivalent to (5) (a)
7. Classic Fixed Effects Model (FEM) - Equivalent to (5) (b) with β_{yz} , = 0 (no z in the equation)

4.1. Selection of the random or fixed effect

The decision between random effects and fixed effects models in econometrics is based on assumptions about unobserved variability and panel data attributes. The fixed effect (FE) model is best fitted when the properties of entity-specific is consistent across time. FE model tackles the problem of unobserved heterogeneity in the model. Following is the model of fixed effect expressed below:

$$y_{it} = {}'X_I + i_t$$

Here i explained the entity-specific effects and t represents the i^{th} entity at time. While on the other hand Random effect holds that the factors/variables have unique entities and have no association with exogenous variables/factors. It also tackles the issue of unobservable heterogeneity as randomly. Following is the equation of the random effect model as ith entity time. The random effect model suggests representing this lack of knowledge through error terms. The Error Component Model assumes that the intercepts for individual cross-sectional units are randomly selected from a larger population with a fixed mean value. Consequently, each country's intercept is considered as its deviation from this mean value.

4.2. Hausman Test

The Hausman test is a useful tool for determining the most suitable regression model between the Fixed Effects Model and the Random Effects Model. FEM results remain reliable when there is a correlation between the regressors and the error term. The main motivation behind using the Hausman Test is to whether the result of the fixed effect model is better than or random effect model.

H0. Random effect is better than fixed effect

H1. Fixed effect is better than random effect

These techniques is best fitted for panel data analysis because they tackle the unobserved heterogeneity in the dana. In our analysis there is a problem with unobserved heterogeneity, that's why we have applied the panel data techniques fixed and random effect model to analysis the data set.

Table 1
Variables and data source.

Variable	Description	Source
GDP_{it}	GDP growth (constant 2010 US $)	WDI
CO_{2it}	Carbon emissions (kt)	WDI
FDI_{it}	Foreign direct investment, net inflows (BoP, current US$)	WDI
IQ_{it}	Institutional Quality is quantified as the average score of various critical dimensions, including Control of Corruption, Government Effectiveness, Political Stability and Absence of Violence/Terrorism, Regulatory Quality, Rule of Law, and Voice and Accountability. This average provides a comprehensive and synthesized measure of a nation's governance institutions' overall effectiveness, transparency, and integrity.	WDI
REW_{it}	Electricity production from renewable sources, excluding hydroelectric (% of total)	WDI
EI_{it}	An energy intensity level of primary energy (MJ/$2017 PPP GDP)	
TECH	In patent applications, residents are used as a proxy for technological innovation.	WDI

5. Data

This study employed annual data covering the period from 1990 to 2022. Information on relevant variables for five chosen South Asian economies—Sri Lanka, Pakistan, India, Nepal, and Bangladesh—was sourced from the World Bank's WDI (World Development Indicators) for 2020. GDP is computed in constant US dollars based on purchasing power parity, while nonrenewable energy represents the percentage of fossil fuel energy in total energy. Similarly, renewable energy is expressed as a percentage of total EC, and FDI is measured as the net inflow balance of payments in current US dollars. This research examines several pivotal variables to unravel the intricate relationship between environmental and economic dynamics. Key areas of emphasis include indicators of economic growth, renewable energy consumption, innovation measures, trade openness, and environmental performance. Every constituent is essential for fully grasping the intricate correlation between sustainable ecological development and economic advancement. A detail of variables construction is given below in Table 1:

Indicators of numerous nations' political, economic, and environmental conditions are exhaustively summarized in descriptive statistics (Table 2). Indicating a moderately skewed distribution with a prominent tail, the average CO_2 emissions are approximately 0.60 units. The Environmental Governance Index (EGI) indicates a moderate degree of environmental governance, as evidenced by its mean score of 3.76 and primarily symmetrical distribution. The data demonstrates that Foreign Direct Investment (FDI) is disproportionately concentrated in a limited number of countries, as indicated by the right-skewed distribution of FDI at an average value of $4.48 billion. A right-skewed distribution of 306 billion USD on average suggests that GDPs are significantly higher in a minority of countries. Indicative of a relatively symmetrical distribution, the mean score for Institutional Quality (IQT) is −0.63.

The mean score of 1358.55 for Political Rights (PAR) indicates a right-skewed distribution, suggesting that only a limited number of nations possess electoral rights that are notably more comprehensive. The distributed data exhibits a rightward skew, implying that certain countries place a more significant emphasis on using renewable energy (RE). The average reliance on RE is 0.55. Detailed examination of the kurtosis values of specific variables reveals that they possess heavier tails. The Jarque-Bera test outcomes and the existence of low probabilities indicate deviations from normality. Overall, the data suggests that substantial disparities and inequities mark the allocation of environmental, economic, and political factors; this highlights the criticality of comprehending these attributes to develop well-informed policies and conduct exhaustive statistical analyses. The cross-correlations in Table 3 discloses the interrelationships among numerous factors in a comprehensive manner. Significantly, an inverse relationship between CO_2 emissions and environmental regulations can be observed, suggesting that regulatory obligations will increase in tandem with emissions.

A notable positive correlation exists between Foreign Direct Investment (FDI), Gross Domestic Product (GDP), and patent applications, underscoring FDI association with innovative and economic endeavors. Moreover, robust positive correlations exist between GDP, patent applications, and renewable energy production, indicating that monetary expansion, innovation, and sustainability are inextricably linked. The correlation between institutional Quality (IQT) and renewable energy production, GDP, and patent applications is moderately positive, underscoring the significance of robust institutions in these sectors. Although most variables exhibit weak correlations with population size, environmental regulations demonstrate a range of factors with positive and negative associations. The cross-correlations offer significant contributions to our understanding of the interconnections of institutional, environmental, and economic elements, shedding light on possible avenues for future research and policy deliberation.

6. Estimation

Within Tables 4 and 5, we present the outcomes of regression analysis based on the fixed effect and random effect model. **GDP**it signifies a nation's Gross Domestic Product (GDP) at time t. **RD**it is a research and development investment for country i at time t. **ER**it denotes the environmental regulations for country i during Time t. **REP**it is an acronym for Renewable Energy in Country i at time t. **FDI** is an abbreviation for foreign direct investment in nation i at time t. **IQ**it is an acronym for Institutional Quality in station i at time t. The population density of nation i at time t is denoted by **PD**it. **TO**it is a measure of a country's trade openness at time t.

We consider CO_2 emissions the dependent variable, serving as a proxy for green growth. Our estimations rely on a fixed effect model, where various model specifications are employed to ensure the robustness of results. We follow a specific-to-general method to comprehend how coefficients and signs change when additional variables are included in each model, spanning from Model 1 through Model 6. The explanation delves into the impact of each independent variable, highlighting the significance of some coefficient estimates and their respective significance levels.

Table 2
Descriptive statistics.

	CO_2	EI	FDI	GDP	IQ	TECH	REW	PoP
Mean	0.596	3.765	20.413	25.516	−0.629	1358.547	0.551	17.113
Median	0.536	4.080	20.398	25.307	−0.688	92.000	0.000	14.948
Maximum	1.292	6.520	24.508	28.375	−0.115	12579.00	5.361	39.016
Minimum	0.198	1.650	14.145	23.355	−1.185	8.000	0.000	5.908
Std. Dev.	0.363	1.437	2.143	1.342	0.326	2826.982	1.220	8.140
Skewness	0.673	0.113	−0.475	0.438	−0.037	2.505	2.718	1.152
Kurtosis	1.920	1.715	3.876	2.343	1.511	8.482	9.525	3.509
Jarque-Bera	11.798	6.744	6.604	4.742	8.800	218.290	285.547	22.028
Probability	0.003	0.034	0.037	0.093	0.012	0.000	0.000	0.000

Table 3
Cross-correlation.

	CO_2	EI	FDI	GDP	IQ	TECH	REW	PoP
CO_2	1							
EI	0.832457	1						
FDI	0.506323	0.216261	1					
GDP	0.654912	0.350731	0.930762	1				
IQ	0.495405	0.224387	0.379242	0.43782	1			
TECH	0.633387	0.328349	0.925232	0.989749	0.505709	1		
REW	0.486176	0.183686	0.925046	0.964252	0.432291	0.969124	1	
POP	−0.21162	−0.37649	0.199587	0.122678	0.447613	0.171459	0.244641	1

Table 4
Regression results based on Fixed Model.

Variable	Model-1	Model-3	Model-2	Model-5	Model-4	Model-6
Tech	−0.2034[a] (3.1726)	−0.1970[a] (1.6935)	−1.9479 (2.7801)[b]	−1.3442[a] (3.9458)[b]	−1.3110[a] (3.1927)[b]	−0.2970[a] (1.3294)[b]
GDP	0.1717[a] (2.0351)	0.3725 (3.2432)	0.3045[a] (3.6913)	0.1761[a] (1.8882)	0.0518[a] (1.5589)	0.1761[a] (2.0132)
RD	−0.1761[a] (3.8611)	−2.7595 (2.2119)[b]	−0.1761[a] (1.7023)	−0.1761[a] (3.2296)	−0.1761[a] (2.5579)	−0.1761[a] (2.3521)
FDI	1.5097 (3.9831)[b]	1.1891 (1.8923)[b]	1.5680 (3.5135)[b]	1.2825 (2.0995)[b]	0.7490 (2.0223)	1.5097 (2.1146)[b]
ER		−1.5097 (4.0132)[b]	−0.0308[a] (1.7931)	−0.3161[a] (3.4324)	0.0261[a] (2.1351)	0.1761[a] (2.3811)
REW				−2.3047[a] (1.7072)[b]	−0.0623 (3.7931)	−0.0308[a] (1.7931)
IQ					−0.1761[a] (4.4132)	−0.0623[a] (3.7931)
Pop						0.1761[a] (4.7831)[b]
R-Square	0.996	0.8446	0.977	0.889	0.881	0.711

The results in the table are based on the ARDL model. T-statistics are presented in parentheses.
***significance at 1 % level.
[a] significance at 5 % level.
[b] significance at 10 % level.

Table 5
Regression results based on random effect Model.

Variable	Model-1	Model-3	Model-2	Model-5	Model-4	Model-7
Tech	0.1025 (3.1836)[b]	0.3780[a] (3.6724)	0.7587 (2.8901)[b]	0.2553[a] (2.7549)[b]	0.2110[a] (2.1738)[b]	0.3780[a] (1.2375)[b]
GDP	−0.818[a] (3.0241)	−0.1834 (2.3523)	−0.1054[a] (2.6712)	−0.861[a] (1.9993)	−0.0419[a] (1.4497)	−0.861[a] (3.0123)
RD	−0.861[a] (2.9611)	3.8474 (3.3117)[b]	−0.861[a] (1.8032)	−0.861[a] (2.3376)	−0.861[a] (3.4487)	−0.861[a] (3.2431)
FDI	0.4078 (2.7921)[b]	0.3971 (1.9732)[b]	0.4690 (2.4124)[b]	0.1934 (3.0774)[b]	0.8570 (3.0332)	1.4078 (3.1156)[b]
ER		1.4078 (3.0123)[b]	−0.0209[a] (1.8721)	0.861[a] (2.5235)	0.861[a] (3.1241)	0.861[a] (3.2911)
REW			−0.9028[a] (1.8083)[b]	−0.0357[a] (3.1348)	−0.2058[a] (5.0123)[b]	−0.0343[a] (2.4315)
IQ					−0.861[a] (2.5123)	−0.0632 (2.8721)
Pop						−0.861[a] (5.8921)[b]
R-Square	0.874	0.767	0.8447	0.799	0.866	0.9112

The table's results are based on the ARDL model. T-statistics are shown in parentheses.
***significance at 1 %.
[a] significance at 5 %, and.
[b] significance at 10 %.

Technological innovation can lead to development and adopting of cleaner and more energy-efficient technologies. Advancements in technology may enhance production processes, reduce resource consumption, and promote the use of renewable energy sources, ultimately lowering CO_2 emissions. Technology may increase efficiency across industries, promoting sustainable practices & growth that is environmentally friendly. The continuous negative association between technological Innovation and carbon dioxide emissions in all models (Models 1–6) suggests that technical improvements help to reduce emissions.

The South Asian region has diverse economies, and Their stages of development are different. Technology innovation holds a significant role in sustainable development. We found in this study that from models 1 to 6 there is a negative relationship between technological Innovation & carbon emissions. Our finding is also consistent with [84]. South Asian Economies have different Socio-Economic Cultures, and they Can tackle climatic issues if they invest in green technology. Economic growth involves economic activities e-i., consumption, and Production. When Economies are expanded, their energy demand (oil, fossil Fuel) increases which leads to increased carbon emissions. This argument supports the environmental Kuznets Curve hypothesis, which postulates that when income increases the environment is initially polluted due to high emissions, but with time CO_2 emissions decline due to high technological advancement. In our analysis, we observed a positive relationship between Economic growth and the Environment (Model 1–6). This study highlights a challenge to mitigate adverse impacts and manage economic development. South Asia has diverse economies, it's a challenge for policymakers how to tackle these issues and what types of Policies should be adopted for Sustainable development.

Investment in Research and Development plays a key role in environmental sustainability. Investment in new technology and R&D leads to Economic prosperity without disturbing the environment. Table 4 shows that this is a negative association between carbon emissions and R&D. It demonstrated that if we invest in R&D Projects leads to diminishing Cor emissions.

FDI also plays a significant role in the economic prosperity of a country. It also affects the environment and creates environmental distortion. Our analysis shows that there is a positive relationship between FDI, and CO2 emissions observed in all models. Therefore, Policymakers need to adept Such environmentally friendly projects to invest in that project which is environmentally friendly. Renewable energy sources (Solar, wind power, water) play a key role in the displacement of fossil and reducing carbon emissions. The use of Renewable energy tech shifts the environment to make sustainability.

Renewable energy variable impact on CO2 emissions shows the Complexity of transitioning to cleaner energy sources. While some models explain a negative association between CO2 emission and renewable energy, some show unexpected results. It is suggested that the policymakers of the South Asian region design effective policing that is Consistently applicable for CO2 emission reduction. Institutional Quality (IQ) plays a key role in environmental sustainability. If the institutions are strong e-i, transparency, Rule of law & Good Governance it leads to economic prosperity. The above table shows that there is a negative relationship between CO2 emission and Institutional quality. This study suggested some implications for South Asian economies and is more focused on effective institutional excellence that can achieve Sustainable development goals.

Higher urban population density can be attributed to increased industrialization, transportation, and energy use. Densely populated places usually face challenges with garbage management and infrastructure, which contributes to increasing emissions. Effective urban planning, sustainable development techniques, and the reinforcement of environmentally friendly structures can all contribute to reducing the environmental effect of a densely populated area.

The positive association between Population Density and Carbon Dioxide Emissions in Model 6 implies that densely populated areas may lead to increased emissions. It suggested that urban planning where there is rapid urbanization in South Asia. Sustainable development strategies must consider the environmental repercussions of high population density. These findings emphasize the complex interaction of factors impacting CO_2 emissions in South Asia. Policymakers must manage these challenges by considering each country's unique characteristics and implementing specialized measures to achieve green growth and sustainable development. The consistently negative coefficients for technical innovation indicate a considerable positive influence on green growth across all models, meaning a decrease in greenhouse gas emissions. This emphasizes the critical importance of technological advances in promoting cleaner and more efficient manufacturing processes, which is consistent with the expectation that advances in technology will be critical catalysts for sustainable development. The high significance levels, such as the t-statistic value of 3.1726 in Model-1 at the 1 % level, highlight the significant reduction in environmental harm enabled by technical advancement.

Green Growth has a moderate impact on the growth of the economy, as indicated by primarily positive coefficients across models. This is consistent with the Environmental Kuznets Curve, which anticipates an initial increase in environmental damage when economic growth occurs, followed by a tipping point. The dynamic association among the different models highlights the link between financial factors and the environment. Negative R&D coefficients suggest that increased R&D expenditure benefits green growth in all models. The consistent observation of a substantial detrimental impact emphasizes the findings' robustness. Investment in Research and Development plays a key role in environmental sustainability. We observed a negative association between carbon emissions and R&D. It demonstrated that if we invest in R&D Projects leads to diminishing CO_2 emissions. Our analysis also shows that there is a positive relationship between FDI, and CO_2 emissions observed in all models. Positive association depicts that FDI increases economic activities which encourage green growth.

Environmental regulations, with largely negative coefficients, have a positive effect on green growth. Effective laws are critical for regulating and mitigating pollution, as well as promoting sustainable development. The constantly negative coefficients show that stricter ecological rules have a lower environmental impact, emphasizing the need for regulatory efforts. The positive influence of renewable energy on green growth is reflected in specific models through negative coefficients. Increased prioritization of renewable energy sources significantly contributes to environmental sustainability, aligning with the goals of green growth. In the last two models, institutional quality positively impacts green growth, as suggested by negative coefficients. Efficiently operating institutions are indispensable for promoting environmentally conscious practices and realizing green growth objectives.

Population density, denoted by positive coefficients, consistently correlates with heightened environmental impact across all models. Intensified resource consumption and economic activity in densely populated regions pose obstacles to realizing green growth objectives. The consistently high R-Square values across models indicate a good fit, suggesting that the selected independent variables collectively account for a substantial proportion of the variation in environmental impact. Model-1 exhibits an exceptionally high R-Square value of 0.996, signifying a considerable capacity to account for the intricacies inherent in the economic-environmental relationship.

The findings might not be directly applicable to other areas or economic contexts due to the narrow focus on Asian economies. As cultural norms regulatory frameworks and economic structures differ greatly among regions different socioeconomic contexts can have a substantial impact on the relationship between the variables. As such although the results offer insightful information for Asian economies care should be taken when extrapolating these conclusions to other settings. The applicability of these findings to various socioeconomic contexts would require more investigation.

Our study has some implications for other economies of the world. The socio-economic characteristics of the South Asian region are different. This study is helpful for the policymakers to understand the socio-economic status of the economies and according to their status, they can design policies for this region. Policymakers need to design state-level policies to encourage private companies to produce energy from renewable sources and also govt focus to on green technological projects to enhance the sustainable environment.

7. Robustness

For enhancing the reliability of the research study we also check the robustness of the data. Using Fixed Effect and Random Effect Models in this study adds a layer of robustness to the analysis, as the two approaches provide complementary perspectives on the relationship between various variables and CO_2 emissions in South Asia. The similarity in the direction of the estimated coefficients across both models is notable. For most variables, the signs of the coefficients, whether positive or negative, consistently align. Fixed and Random effects models are two different models, and both indicate that there is a Positive Association between economic growth and carbon emissions. Research & Development Coefficients are negative which supports green growth.

The coefficient of FDI is positive indicating a Positive influence on green growth. If we look at both models Fixed and Random effect the Coefficients of environmental regulation are negative, which helps in the diminishing of Corban emissions. Renewable energy also depicts a negative association with the environment. It means supporting green growth. The sign of Institutional Quality (IQ) is also consistent with Economic Theory. The finding shows a negative association between IQ and CO2 emissions. Improve the quality of the institutions can help in the reduction of Corban emissions. The high R-Square values across models strengthen our findings, indicating that the selected independent variables are well-suited to explaining the variability of CO2 emissions.

This consistency strengthens trust in the study's findings and their application to South Asia. Finally, the coherence and consistency of computed coefficients across Fixed and Random Effect Models demonstrate the robustness of our results. This broadens the implications for South Asian policymakers as they navigate the hurdles of green growth while taking into consideration each country's distinct characteristics.

Figures 2 (a) and 2 (b) explains the sensitivity analyses of CUSUM and CUSUMsq. The outcome of both tests (CUSUM and CUSUMsq) shows that the data is stable because the data lies between the lines. Thus, it shows that data are reliable and stable at a 5 percent significance level.

8. Conclusion and recommendations

In the existing study, we are investigating the factors that are affecting corban emissions, which behave as a measure of sustainable development, with an emphasis on the South Asia economies. We used both the Fixed Effect and Random Effect models, as well as a robust estimate technique, to ensure the validity and correctness of our findings. The primary goals of this study were to establish an in-depth knowledge of the complicated connections between technological innovation, economic growth, FDI, expenditures in research and development (R&D), energy efficiency, institutional quality, population density, and greenhouse gas emissions. Through a systematic progression from specific to general models (Model-1 to Model-6), we determined the impact of additional variables on the coefficients and their significance levels. Technological innovation has been recognized as a significant driver for environmentally sustainable Development in South Asia, as indicated by consistently negative coefficients in all models. The findings demonstrate that technological advancements significantly impact the reduction of CO_2 emissions. This demonstrates the ability to promote innovation as an approach to addressing environmental issues throughout the region's different economies. The complex connection between economic growth based on the Environmental Kuznets Curve and CO2 emissions demonstrates the difficulty of distinguishing regional ecological growth from economic growth. We Found a strong reliable association between Investment in R&D & carbon emissions. Investment in Research & development brings Green technology to a country that supports a Sustainable Environment. FDI also plays a key role in Economic Prosperity by Investing in projects that are environment-friendly. Green projects will help diminish carbon emissions. The findings also show that the signs of environmental regulations & Institution Quality support economic theory. There is a negative association between Institutional quality and CO2 emission. Strong institution secure Sustainable environment.

Although this study offers insightful information about how Technological developments in renewable energy sources and institutional quality affect carbon emissions in the economies of South Asia (Pakistan India Bangladesh and Sri Lanka) there are several important limitations to take into account. The results may not be as generalized to other regions with different socioeconomic

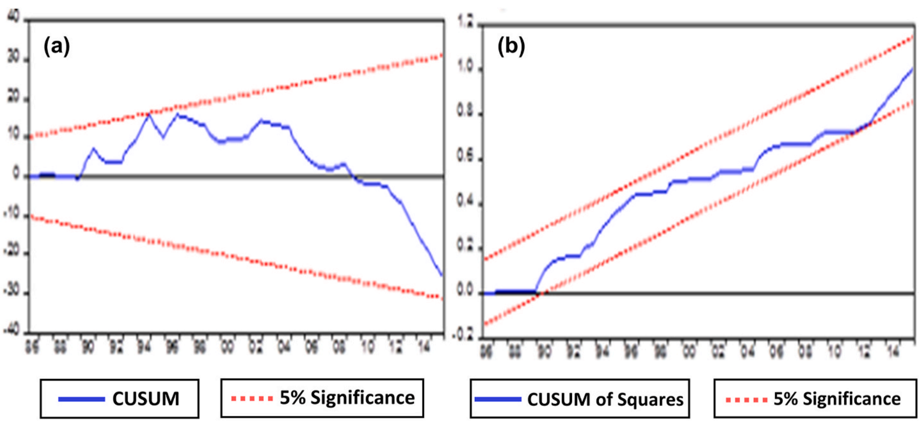

Fig. 2. Sensitivity analysis: (a) CUSUM and (b) CUSUMsq.

contexts due to the narrow focus and the use of data from 1990 to 2022. Furthermore, the study uses a quantitative research design with fixed and random effect models which although reliable might not fully capture all the subtle interactions and qualitative facets of the difficulties in advancing renewable energy. The use of historical data also raises the possibility that the quickly changing Technological and policy environments have not been properly taken into consideration. Finally, although the sensitivity analysis suggests that the data are stable and reliable more research with a wider geographic scope and a variety of methodological approaches would be helpful to confirm and expand these findings.

Many specific policy instruments can be recommended to prioritize renewable energy development in the region based on the findings of your study which highlight the complex relationships between Technological innovation economic growth FDI research and development (R&D) expenditures energy efficiency institutional quality population density and greenhouse gas emissions in South Asia. **1. Feed-in Tariffs (FiTs):** By putting FiTs into place renewable energy producers can receive guaranteed payments for the electricity they produce and feed into the grid. If this strategy is implemented in the region by enhancing investment in green renewable projects. 2. **Tax incentives:** The government should give incentives to private sector investors who produce energy from renewable sources. Through this, they will attract and increase investment in green projects which will be helpful for a sustainable environment. **3. Institutional Quality Enhancement:** The Government should enhance the quality of the institutions. There is a need for strict action against those institutions that release more carbon emissions into the environment and should pay more for environmental sustainability. Through strong institutions we can achieve a sustainable environment. 5. **Lounching Green projects:** The government should focus on Lounching Green projects and promoting Research and Development through which we can enhance the environmental sustainability in the South Asian region. These policy recommendations are based on our findings which focus on technological innovation and sustainable institutional quality that can enhance environmental sustainability and it helpful in decreasing greenhouse gas emissions.

Our research study significantly highlights the dynamics that influence carbon emissions in the South Asian region. Research also suggested that Policymakers should consider each country's characteristics and adopt policies that support Green growth. Additionally, this study also contributes to and highlights the different factors that influence environmental sustainability in this region. This increases our existing knowledge and helps to adopt policies for long-term sustainability.

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Data availability statement

The data sets used during the current study are available from the corresponding author upon reasonable request.

Consent to publish

All authors agree to publish the manuscript.

CRediT authorship contribution statement

Fan Junliang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lei Dang:** Writing – review & editing, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Xiaoling Cheng:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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