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The impact of urbanization, energy consumption, industrialization on carbon emissions in SAARC countries: a policy recommendations to achieve sustainable development goals

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Abstract

This research delves into the inter-relations between urbanization, industrialization, energy consumption, and carbon dioxide emissions (CO_2) in SAARC countries, and emphasizes their impacts on the sustainable development goals (SDGs). As the regional importance grows because of the fast urban and industrial development accompanied by the high energy consumption, such analysis becomes of great significance in the of environment and policy planning for the SAARC region. Technically, the study uses advanced econometric approaches, including the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model, and if it is necessary, second-generation unit roots and cointegration tests may be used as well. The process is what helps you have a good look at the long-term relationships and dynamics among the variables in mind. The main results demonstrate that CO_2 emissions from urbanization and industrialization are much higher, so there is a compelling reason to look for ways to make our urban and industrial policies more sustainable. Inversely, power consumption, especially from fossil fuels, becomes a major emissions contributor, implied by the fact of transitioning to renewable energy sources. Among the effects of population growth, natural resource rent, and electrification on emissions mitigation, several policy intervention domains seem promising. To achieve sustainable development goals for SAARC countries, the member nations must collaborate on sustainable practices in urban planning, energy consumption, and industrial activities. The research is focused on renewable energy integration and sustainable urban planning; therefore, the research provides essential knowledge for policymakers to design strategies that are supposed to minimize negative impacts on the environment but also bring economic growth. Such findings and recommendations are the keys that are going to help in shaping the environmental policy and the strategic growth of the SAARC region while ensuring harmony between environmental and economic development.

Keywords CO_2 Emission · CS-ARDL · Industrialization · Environment · Urbanization · SDGS · SAARC

Abbreviations

SDGs	Sustainable development goals

Extended author information available on the last page of the article

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SAARC	South asian association for regional cooperation
CO_2	Carbon dioxide
CS-ARDL	Cross-sectional autoregressive distributed lag
CCEMG	Common correlated effects mean group
STIRPAT	Stochastic impacts by regression on population, affluence, and technology
GMM	Generalized method of moments
CIPS	Cross-sectionally augmented IPS
UN-SDGs	United nations sustainable development goals
ARDL	Autoregressive distributed lag
AMG	Augmented mean group
MG	Mean group
PMG	Pooled mean group
DFE	Dynamic fixed effects
NDCs	Nationally determined contributions
GDP	Gross domestic product
FDI	Foreign direct investment
ICT	Information and communication technology
CADF	Cross-sectionally augmented dickey-fuller test
SH	Slope heterogeneity
CSD	Cross-sectional dependence
LFF	Logarithm of fossil fuel consumption
LCO_2	Logarithm of carbon dioxide emissions
LPOP	Logarithm of population
LGDP	Logarithm of gross domestic product
LURB	Logarithm of urbanization
LIND	Logarithm of industrialization
LELEC	Logarithm of electricity consumption

1 Introduction

It is fundamental to note that technological and economic innovations notwithstanding, rising levels of CO_2 emissions and environmental depletion continue to be a vital global concern. In this vein, we must work together to find viable solutions and focus on the welfare of Mother Earth for posterity. The rapid urbanization, industrialization, population growth, and fossil fuel usage among SAARC member countries in high-growth areas are fascinating. There is a crucial need for sustainable development solutions and collaborative efforts among nations to address the challenges at hand effectively (Khaliq & Mamkhezri, 2023). Considering that the SAARC region is home to more or less 21% of the global population, it becomes a prerequisite for understanding this complex issue to identify what problems climate change has created before these countries. The world environmental bins of support are articulated under the UN-SDGs (Das et al., 2023a, 2023b). Conversely, in SAARC countries, it is of greater worry due to the industrialization and urbanization levels that these states have passed through (Destek et al., 2023). From the overcrowded streets of Mumbai to the polluted skies above Dhaka, environmental degradation caused by economic development in SAARC is irreversible.

The most significant carbon dioxide (CO_2) emitters are India and Pakistan, two of the most populous nations in this world, due to their high reliance on fossil fuels and other non-renewable sources. Dhaka, the second most polluted global city, faces a significant challenge. (Ullah et al., 2021a, 2021b) stated that the developing large energy-consumptive infrastructural projects needed for a growing population will impede the transition into renewable forms. Moreover, according to (Xiaoman et al., 2021), claim that there is no association between the increase in gross domestic product in SAARC and reduced CO_2 emission levels does not hold. (Xu et al., 2023) predicts that the urban citizenry of South Asia is estimated to rise to 250 million by 2030. As for the elements of nature in SAARC countries, the interaction lies between sustainable environmental technologies and staying away from fossil fuels, which coincides with the acceleration of urban economic growth (Azam et al., 2022). Deforestation in Pakistan is being done at an alarming rate, coupled with the rampant depletion of biologically viable ecosystems, hence portending severe challenges for sustainable options. Therefore, this study focuses on the complex interrelationship between population growth rate, urbanization process of people's lifestyle, industrialization development, fossil fuel consumption resource depletion, electricity consumption, and CO_2 emissions for SAARC counties with a response to those above intricate challenges.

Utilizing advanced methodologies, such as the Cross-Sectional Autoregressive Distributed Lag (CSARDL) estimate method, seeks to contribute academically to this critical policy debate on environmental conservation.This complies with the SDGs and also regional specificity of not only socio-economic interrelationship but also the culture one. In this ongoing international discourse regarding the value of sustainability, it becomes increasingly reasonable to question the specifics about how SAARC countries urbanize and also use fossil fuels (Fang, 2023). These countries' main objectives are to develop environmentally friendly infrastructures and also at the same time economically viable owing to the level they wish to attain in a way that no human and human industrial plantations development. Therefore, this research aims to fully comprehend the intricacies within these dynamics so that policy can be made that appropriately balances utopian needs for ecological sustainability and the need for progress. The increasing level of use of fossil fuels, as demonstrated by the recent increase in global consumption of petroleum oil, lignite, and natural gas, is a clear reflection of how much most SAARC nations' are dependent upon them due to their impressive economic growth recently achieved (Pandey & Asif, 2022). The region's stronghold on fossil fuels manifests in compounding environmental issues already confronting it, such as air pollution and CO_2 emissions, making it more susceptible to volatility in global energy costs. The urgency of this situation is evident in the fact that urbanization is driving unstoppable energy needs within cities like Karachi, Lahore, Colombo, and Delhi.

Using fossil fuel as a source of energy in the SAARC region threatens damage to local ecosystems and uses up oxygen, water, and sediment. More industrialization was related to high prevalence of cardiovascular and respiratory conditions (Li & Wang, 2023; Yu et al., 2023). These problems draw attention to the importance of Sustainable Development Goals (SDGs), Goal 3, Good Health and Well-being, Goal 7, Affordable and Clean Energy, Goal 11, Sustainable Cities and Communities, and Designation 13, Climate Action in SAARC. However, given this region's unique regional geopolitical and socioeconomic realities, a holistic approach is required to deal with SAARC's energy issues or environmental challenges. Promoting public awareness, reforming policy guidelines about environmental management and development strategies, and advancing collaborations through technological innovation are all crucial to steering the region toward a sustainable future (Latief et al., 2021). By incorporating renewable energy sources in the region's energy pool, it is possible to mitigate the negative implications of burning fossil fuels. A rise in biofuel imports will also be driven by a massive breakthrough of wind, solar, and hydroelectric power; this growth opens up opportunities to reduce those dependencies on fossil raw materials standing now as the global trend towards environmentally friendly production through renewable energy supplies.

Adebayo (2022), developed an indicator for the energy-environment relationship in Spain using the load capacity factor as a measure. Their research has shown that REC improves environmental conditions both in the long and short term, whereas fossil fuels have the opposite effects. Subsequently, FDI inflows contribute to environmental quality, but ECI slows down this process over short and long periods. Adebayo et al. (2024), in this respect, study Sweden's positive achievements concerning the mitigation of CO_2 emissions and ecological footprint, stressing the main role of energy efficiency R&D investments and technological advancements in the process. They provide for a strategic move towards energy-efficient technologies. In the United States, the winners of Adebayo and Özkan (2024b) explore how social and economic conditions, ecological innovations, and renewable resources affect CO_2 emissions. Their research identifies those crucial factors for developing environmental strategies.

The practical opportunity to implement such measures in other developing territories might serve as an impasse and show that modern global challenges and issues are interrelated. The focus of the study on environmental implications and fossil fuel consumption in the SAARC region is paramount, especially considering its high relevancy. Given the immediate need for action towards understanding, it goes beyond the statistics and discourse of policies (Azam et al., 2022). This research focuses on the connectedness between industrialization, population growth, urbanization, and energy consumption to develop a plan for building greater resilience toward sustainability in the future (Rasheed et al., 2022). The intricate relationship between urbanization, environmental degeneration, and fossil fuel consumption in the SAARC region is an issue of scholarly interest and presents a critical existential predicament (Chen et al., 2023). Therefore, the complex dynamics studied in this research help define sustainable paths of future development and provide ideas and knowledge reaching beyond SAARC's borders. In a bid to make a significant academic contribution to international discussions about sustainable growth and environmental management, this article recognizes the shared responsibility we have for the planet.

Even though technology is at its peak and achieving economic stability in this modernized world, the overall effects of carbon dioxide increment and deterioration are significant. After the COP26 summit, it also became more apparent that international collaboration is necessary if sustainable solutions are to be developed. Nonetheless, regarding member states of SAARC, this argument has much truth as they have some similarities, including a quick rise in urbanization and industrialization rates, an increase in population level, and high use levels of fossil fuels. Given that the SAARC region hosts over 21% of the global population, it is wise to understand how these complicated dynamics interact with climate change issues facing nations in this zone. The goals and commitments under COP26, such as more NDCs and continued calls for higher climate action, pose heavy implications for such countries. The conclusions of the COP26 that stress global obligations to sustainably resonate with the UN-SDGs (Razzaq et al., 2023).

The pressing issue of fossil fuel usage during urbanization and industrialization has caught the attention of SAARC nations. As per the report by Kartal et al, (2023), there is a growing concern among these nations regarding the impact of fossil fuels on the environment. It is high time that we took notice of this concern and took the necessary steps to reduce the use of fossil fuels to ensure a sustainable future. The adverse environmental effects of economic development in SAARC vary from the congested streets of Mumbai to the toxic air above Dhaka. Fossil fuels and other non-renewable energy sources are another major cause for CO_2 emissions to be released into the atmosphere; the dominant issue about these can be related to India's weaknesses because India's 17 peculiarities were reliant on fossil fuel power rebuilt capacity at thermal plants. One of the central ideas that COP26 tried to pass was elements such as a significant need for infrastructure supported by electricity and feeding an increasing population hindering the transition into renewable energy sources (Ullah et al., 2021a, 2021b). (Xiaoman et al. (2019) also note that the lack of a positive relationship between SAARC's GDP growth and reductions in CO_2 emissions was discussed during COP-26, an international conference dedicated to sustainable economic processes.

Wang et al. (2021) focused on the influence of environmental policy, green energy, and tax on acquiring zero CO_2 emissions stock. In addition, natural resources and financial growth continue to threaten the carbon neutrality agenda since these forces increase CO_2 emissions. Adebayo and Alola (2023) note that the more significant impact on renewable energy integration occurs for quantiles above some threshold, suggesting a significant effect at higher levels. The second variable is the correlation between renewable resources and household energy efficiency, which has values generally lower than the first quartile. In addition, economic growth and higher per capita energy consumption together lead to a significant increase in renewable energy use that reveals visible patterns, particularly among the top three quintiles.

Regarding the effects on natural gas consumption, there are also observable dampening in various quartiles for household energy efficiency and retail electricity prices. To be more precise, household energy efficiencies are characteristic of upper-quartile variables when the lower ones are included in consideration. Xiaoman et al. (2019) argue that coal efficiency moderates CO_2 emission levels in different periods, while long-run gas statistics are negatively influenced by uncertainty about climate policy. Moreover, ecology quality is also better in the short- and medium-term; green energy consumption and innovation help decrease CO_2 emissions.

Adebayo and Alola (2023) revealed that the negative effect of retail costs on renewable energy uptake is more pronounced in higher quantiles; thus, the impact remains critical at more significant values. The aims include examining the relationships, assessing their compatibility with various SDGs, and developing a new model framework by adapting the STIRPAT model. The nature of the study is one-of-a-kind because it provides an all-inclusive view that, apart from promoting proper policies for sustaining industrial progress and development, focuses on how healthy regions are faring about global sustainability goals. The importance of environmental economics and sustainable development is due to their policy applications, the analysis that considers a significant amount of data in total using econometric methodology.

A research framework that merges the EKC hypothesis with the SDGs is employed to analyze the linkages between economic development, environmental degradation and sustainability in the SAARC region. The analysis is conducted through the use of sophisticated methods such as CSARDL to establish the causal relationship between the variables. Technological innovations, renewable energy adoption, international cooperation, public awareness and environmental policy reforms which are focused on overcoming environmental challenges and promoting sustainability are key areas of concentration. The framework lays out the policy model and is an integral part of the global discourse on environmental conservation and sustainable development.This study is also consistent with the COP28 conference which aims at the global climate change problem by proposing measures that promote energy saving and use of renewable energy sources.

Regarding building energy consumption, China plays a predominant role, and the consumption of the building sector in the country is among the biggest factors contributing to the country's overall energy consumption (Huo et al., 2018; Liu et al., 2022). As a result of this, China's energy consumption in the building sector is one of the most important factors that the COP28 goals aim to achieve.The study is centered on the determination of the role played by urbanization, industrialization, and CO_2 emissions on the environment, and this is in the hope of achieving economic growth while sustaining the environment. Advanced econometric models like the CS-ARDL model and the new generation unit roots and cointegration tests are used to assess the long-term impact of socio-economic factors on environmental decline. Innovation is using an integrated analysis framework to model a variety of factors and to provide data-driven policymaking tools, which are based on empirical analysis, to support sustainable development for SAARC countries.

1.1 Significance of study

The study comprehensively analyses the relationship between urbanization, industrial growth, population expansion, and energy consumption in SAARC nations. The findings have immediate consequences for environmental policy, demonstrating the need to pursue economic policies that fit with global SDGs. By recognizing the complexities specific to SAARC, having many citizens and locations, the research develops our understanding of materials connected with the organizational climate in these places. The analysis pinpoints the importance of fossil fuel consumption for environmental degradation beyond numbers as it relates to urbanization, industrialization development and population growth. Health risks, especially respiratory and cardiac complications, highlight the significance of Goal 3 for SDGs and other sustainability issues. Considering the imminent threat from the overconsumption of fossil fuels, urbanization and environmental degradation, this research proposes global cooperation using technological innovations, policy reforms and public sensitization. Concerted efforts are required to fight this menace since the world's destiny cannot be left alone. This research study significantly contributes to the international discussion on sustainable development and environmental preservation. The results have valuable insights beyond nationalism, meaning the ownership of planetary health and sustainability.

This issue is a global public concern, and growing public awareness of environmental issues has shed light on factors that lead to this. Economists have focused on how economic growth affects environmental factors in the past decade. Researchers have paid much attention to the link between economic development and the environment, especially since the 1970s. From this perspective, the decline in environmental quality during the early stage of economic development is consistent across all studies, which then improves as the economy progresses. Therefore, in the initial stages of development, environmental pressure increases faster than income. On the contrary, as development advances, GDP increases. The relationship between changes in income and environmental quality is known as the Environmental Kuznets Curve (EKC). The inverted U framework is named after Kuznets (1955), who posits a parallel relationship between economic development and income inequality.

As the industrial revolution began, resource development was given priority over ecological degradation, and people became more interested in employment and income, even at the expense of clean air and water, so pollutant levels shot up (Dasgupta et al., 2002). Development invariably leads to pollution and depletion of natural resources, which enhance the existing environmental burden. People are either too poor to pay for mitigation, or they do not care about the impact of growth on the environment. When incomes rise during a later stage of industrialization, people pay more attention to environmental issues; administrative bodies become better at their operations and pollution levels decrease. As a result, the EKC hypothesis states that it is possible to establish a strong positive relationship between environmental stressors such as pollution intensity concentrations, flow rates, resource depletion, and economic development. EKC show the evolution of a measurable environmental quality as the human condition improves. EKC in other words, are mathematical abstractions that represent basic features of human activity as a whole in the two-dimensional space. The EKC argues that plotting pollution indicators against per capita income produces an inverted J-shaped curve.

Based on the results of EKC, environmental augmentation and economic progress may be complementary under specific policies. First, income growth makes it easy to implement proper environmental policies. In particular, before policy adoption, understanding the characteristics and causal relationship between economic development and environmental quality becomes paramount (Cialani 2017).

2 Literature review

Numerous academic debates exist concerning the causes of environmental degradation, with industrial expansion, population growth, urbanization, economic development, and energy consumption being the primary factors examined. Between 1980 and 2008, (Rahman et al., 2022) evaluated the effect of growing populations and industrial growth on CO_2 emissions in four more significant SAARC countries. By focusing on Goal 9 (Industry, Innovation, and Infrastructure) of the SDGs, their research attributed these emissions to rising industrialization and population growth. (Yang et al., 2022) investigated the relationship between urbanization and environmental degradation between 1982 and 2013. Their findings indicate that the relationship between Bangladesh and India is negative, but Sri Lanka is optimistic. Using the STIRPAT model, (Sufyanullah et al., 2022) extended the discussion by suggesting that the increasing population and GDP per capita were responsible for CO_2 emissions in SAARC countries from 1994 to 2013. (Qin et al., 2021) found that urbanization in the SAARC countries contributed to decreased CO_2 emissions between 1996 and 2015. (Adeleye et al., 2023) investigated the complex interrelationships between trade, urbanization, industrialization, and CO_2 emissions, demonstrating how globalization, urbanization, and financial development contributed to the increase in emissions. (Mentel et al., 2022) analyzed how industrialization and energy utilization affect pollution and found that these factors significantly contributed to environmental degradation in SAARC nations.

Financial globalization, economic growth, economic policy uncertainty, and oil consumption are responsible for the perilous state of ecological quality and carbon emissions. In a Brazilian study using Quantile-on-Quantile Granger Causality (QQGC), those factors were found to forecast them across different quantiles, and they pointed to the problem of efficient ecological policies that need to be developed (Adebayo, 2024; Adebayo & Özkan, 2024a). As for the United States, the amount of hydroelectric power and natural gas emissions on the short-, medium-, and long-term scales could be different due to the need for alternative energy sources to be available as soon as possible (Adebayo, 2024). The research on how the BRICS countries can use new technologies, and renewable energy, and protect their natural resources to promote low carbon emissions and environmental sustainability made the results stand out (Adebayo, 2022). In summary, a study that devoted space to uncertainties and gave a policy framework for promoting renewable energy uptake along with the effective achievement of climate change goals would be helpful (Alola & Adebayo, 2023a).

(Amin & Song, 2023) furthered our comprehension of the relationship between GDP growth, CO_2 emissions, and other environmental variables. (Kaiser, 2023; Khan et al., 2023a, 2023b; Pan et al., 2023) investigated the effect of natural resources, government, and finances on the environment and economic development in SAARC nations, highlighting the crucial role of governance in improving environmental quality. (Wang et al., 2022) extended the discussions to a variety of nations and periods, providing numerous insights into the dynamics of CO_2 emissions, energy consumption, urbanization, and industrialization. Multiple interconnected degrading factors pose an undeniable danger to our planet's environment. The intricate interplay between these factors necessitates a multifaceted approach to resolve them effectively (Hasan & Du, 2023; Khan et al., 2023a, 2023b; Wang et al., 2023). Each issue, such as climate change, pollution, deforestation, and exploitation, exacerbates the others, creating a cascading effect that threatens the delicate balance of our ecosystem. For the benefit of all life on Earth, we must work together to lessen the harm that these factors are causing (Raihan & Tuspekova, 2022).

Nevertheless, it also recognizes the inconsistencies and gaps in a lot of earlier studies, such as ignoring the effect of SH and CSD tests as well as conventional panel estimators (Amin & Song, 2023). However, many studies have shown that environmental degradation is very complex because of the various approaches and results obtained. The SAARC region faces several environmental problems, including deforestation, industrialization, urbanization, and a high population that puts high pressure on its ecosystems (Anwar et al., 2022). The effects of SDG-13 have increased the frequency of many cyclones, droughts, and floods in that area (Anwar et al. Worrisome problems include a lack of water, air pollution, and waste problems. Unfortunately, these environmental problems have far-reaching physiological, socioeconomic, and social implications on the population of this region (Amin et al., 2023; Singh et al., 2023).Solving these problems calls for concerted efforts to ensure that there are sustainable development practices that promote economic advancement without compromising the environment. The studies have also investigated the correlation between industrialization, urbanization, deforestation rates, and their relation to environmental impacts. (Nathaniel & Adeleye, 2021) applied the Granger causality test to explore the environmental impact of industrialization and urbanization in European countries. The research showed that the non-sustainable programs facilitate sustainable suburban growth and cause harmful environmental degradation.

Moreover, technological development significantly contributes to worsening or improving environmental problems. Another study (Mehmood, 2022) utilized the generalized method of moments (GMM) estimator to study the patterns of technological innovation and CO_2 emissions in China and found that many technological innovations within some industries could cause an increase in carbon dioxide emissions. Hence, it is imperative to formulate tactical plans that align with environmental goals. Policy implementation and governance play a very crucial role in this discourse. (Mehmood et al., 2022) They applied the VECM model to evaluate the role of legislative and regulatory actions in the deterioration of the natural environment in SAARC nations from 1990 to 2015. This highlighted the necessity for government intervention, as a correlation was observed between the effectiveness of governance and decreased levels of CO_2 emissions (Khan et al., 2023a, 2023b).The study used panel data analysis to understand the long-term effects of renewables within OECD countries from 1990 to 2012. They used the ARDL cointegration technique while studying the relationship between economic growth and environmental degradation and revealed that renewable energy reduces both effects (Yu et al., 2022). The analysis of the effect of financial products on CO_2 emissions in Pakistan was conducted through the use of the ARDL cointegration method. In this analysis used the ARDL cointegration method to evaluate the effect of financial products on CO_2 emissions in Pakistan over the period 1975–2014.

The study highlights a complex relationship between the financial development and the environmental problems that are able to alleviate or escalate depending on the economic setting and implemented policies. In their research, (Musah et al., 2022) investigated how agriculture has influenced the quality of the environment in Nigeria in the period 1981–2014 using Nigerian data and the Johansen cointegration method. Their study showed that obsolete farming methods and widespread chemical use are major causes of environmental pollution (Chopra et al., 2022). The study by (Ahmed et al., 2022) investigates the impact of climate change adaptation strategies in sub-Saharan Africa between 2000 and 2019. They concluded, utilizing a model with fixed effects, that while targeted adaptation strategies can result in environmentally sustainable practices, they must be regionally tailored (Amin & Song, 2023).These additional studies strengthen and expand our knowledge of environmental degradation (Alshammry & Muneer, 2023; Chen et al., 2023). They underscore the multifaceted nature of this issue, which includes diverse economic sectors, technological advances, government policies, financial practices, agricultural activities, and regional specifics. The literature emphasizes the need for sustainable, integrated approaches that consider the complex interaction of variables.

2.1 Literature gap

Nevertheless, tourists' movements are limited due to environmental degradation and globalization. On this side, transport services also drive-up CO_2 emissions through economic growth and tourism. Khoshbakht et al. (2013) have identified positive changes in the tourism industry from renewable energy, economic growth, and transport sector development. While globalization and clean energy sources have somewhat helped lower CO_2 emissions, these effects are insignificant, betraying a failure in generating renewable currencies due to missing out on positive spillovers from globalization. Based on this, we recommend that the region to realign its tourism industry. Hence, it has pro-environmental features such as using renewable energy sources and more stringent environmental laws. In their study, Adebayo and Alola (2023) identified several factors associated with an increase in ecological footprint: openness to trade, political risk, economic growth rate of nations, urbanization and financial risks.

Further, the researchers found that renewable energy and economic and financial risks improve environmental quality. This study showed a causal relationship between political risk, economic growth, urbanization and trade openness concerning the ecological footprint. In their study, Adebayo and Alola (2023) investigated the possibility of dissimilar effects by DMC biomass, fossil fuels, and metallic ores—on significant greenhouse gas emissions. They validated the EKC hypothesis for MINT economics; these emissions can be categorized as industrial GHG, waste management, and gross emissions aggregated from the agriculture sector. It was revealed that metallic ores DMC contributes to the emission of greenhouse gases, while biomass and fossil fuel DMC contribute less GHG over time. The long-run elasticity of biomass DMC is 0.04 regarding reduced AGHG and WGHG response. At the same time, only IGM effects are generated with metallic ores by an approximately nonelastic factor of about 0.24.

3 Research hypothesis

Hypothesis 1 There is a strong correlation between fossil fuel consumption (LFF) and carbon dioxide emissions (LCO_2) in SAARC countries.

Hypothesis 2 In the SAARC region, urbanization (LURB) and industrialization (LIND) give rise to a positive influence on CO_2 emissions.

Hypothesis 3 In SAARC countries, there is a positive relationship between economic growth (LGDP) and CO_2 emissions.

Hypothesis 4 In SAARC countries, electricity use (LELEC) relates to carbon dioxide emissions (LCO_2).

Hypothesis 5 The SDGs variables show considerable correlations, suggesting the region's progress towards achieving these goals.

Hypothesis 6 The modified STIRPAT model in the novel framework allows us to gain a more subtle understanding of how various factors affect CO_2 emissions by SAARC countries.

4 Methodology

4.1 Data

The research focused on the SAARC nations data sample, including Nepal, Bangladesh, India, Pakistan, Sri Lanka, Afghanistan, Bhutan, and Maldives are on the list. These nations are essential players within the SAARC framework, collaborating on regional integration and sustainable development. Our work focuses on SAARC because it is significant for the region, which includes countries with different problems of air pollution from fossil fuel consumption and urbanization. The population, demographics and economic structures of this region provide a lot to learn about the interplay between growth of population urbanization and industrialization. The results of our research are consistent with SAARC policy priorities that directly contribute to the regional discourse and decision-making processes. However, the collaborative capacity within SAARC offers an opportunity for informing joint initiatives on environmental issues. The consistency of data among SAARC countries improves the dependability of our study, which provides an opportunity for comprehensive analysis on factors that influence environmental sustainability. While our contribution is particular to the SAARC, its results have universal significance in promoting a holistic understanding of sustainable development and environmental concerns.

Table 1 Variables names and details

Variables	Variable name	Logarithm
*CO_2	CO_2 emissions	LCO_2
POP	Population	LPOP
GDP	Economic growth	LGDP
URB	Urbanization	LURB
INDU	Industrialization	LINDU
FF	Fossil Fuel Consumptions	LFF
ELEC	Electric power consumption	LELEC

*Represent the dependent variable

Table 2 Descriptive statistics of key variables for SAARC countries

Variables	Number of observations	Mean	Standard deviation	Minimum	Maximum
LCO_2	205	9.397	2.713	4.875	14.72
LPOP	245	16.73	2.78	11.73	21.07
LGDP	214	24.15	2.218	18.93	28.65
LURB	245	15.18	2.886	9.75	20.01
LIND	216	3.08	0.372	1.805	3.815
LFF	222	1.772	2.137	0.0026	6.42
LELEC	217	4.835	1.13	1.755	6.7

This study characterizes "Fossil Fuel Consumption" as the revenue generated from extracting and refining fundamental materials such as coal, oil, natural gas, and timber. After deducting the cost of extraction, this is the country's net financial benefit. This concept is consistent with the SDGs, particularly Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action), reflecting the global effort to reduce dependence on nonrenewable energy sources. In empirical studies, FF are frequently used as predictor variables to examine their influence on various socioeconomic outcomes. Among these crucial areas are economic development Goal 8, income inequality (Goal 10), political stability Goal 16, and environmental degradation Goal 15. The variables considered for this study, their descriptions, and how they correspond to the SDGs are listed in Table 1. In addition, Table 2 contains descriptive data for these variables, including multiple observations, the mean, standard deviation, and the maximum and minimum values for seven variables (LCO_2, LPOP, LGDP, LURB, LINDU, LFF, and LELEC) for SAARC countries. These descriptive statistics are not merely numerical representations; they provide policymakers and researchers with a comprehensive awareness of the distribution of the variables and their potential interrelationships. These data may steer SAARC's united pursuance of the SDGs, indicating a geographical region's combined response to global challenges.

The following tables summaries key variables that reflect economic expansion, urbanization, industrialization, fossil fuel consumption, and electricity accessibility. These align with specific SDGs and provide insight into the region's endeavors toward sustainable development. LCO_2, with 205 observations representing the log of CO_2 emissions, emphasizes climate action and aligns with SDG 13, with a range of 4.875 to 14.72 and a mean of 9.397. LPOP corresponds to SDG 11, which emphasizes sustainable cities and communities and has a mean value of 16.73 across 245 observations. LGDP represents regional economic growth under SDG 8, with values spanning from 18.93 to 28.65 across 214 observations. LURB captures the dynamics of urban population growth, which is significant to SDG 11 with a mean value of 15.18. LIND, which consists of 216 observations with a mean value of 3.08, reveals industrial production levels essential to SDG 9's focus on industry, innovation, and infrastructure. LFF, which represents the log of fossil fuel consumption, conforms to SDG 12 and ranges between 0.00261 and 6.42 with an observation of 222. LELEC reflects SDG 7 and consists of 217 observations with values ranging from 1.755 to 6.7. Collectively, these figures provide a comprehensive perspective on the region's progress toward achieving the SDGs, enabling researchers and policymakers to develop strategies to promote collective growth, sustainability, and harmony among SAARC nations.

4.2 Theoretical framework

The aim of this research is to create a unique methodological approach to studying the impact of the urbanization process, industrialization, power consumption in the form of electricity, and sources of fossil fuel business on the phenomena of damage to environmental resources demonstrated in Fig. 1. For the variables given, we employ a modified version of the popular STIRPAT model. The pope IPAT model was created by Holdren and Ehrlich in 1974 as Stochastic (ST) effects (I) through regression (R) on population (P), affluence (A) and technology, with further refinement in 1997 by Dietz and Rosa. It is a proven practice of determining the sources that are contributing to environmental deterioration. (Tariq et al., 2022) concluded that the IPAT model faced pitfalls due to its failure to consider important variables such as human behavior and choices and non-linear effect of fundamental environmental variables. Approximately twenty years hence, STIRPAT was created to address the limitations of IPAT. It is robust across numerous data formats, such as cross-sectional, time-series, and panel structures

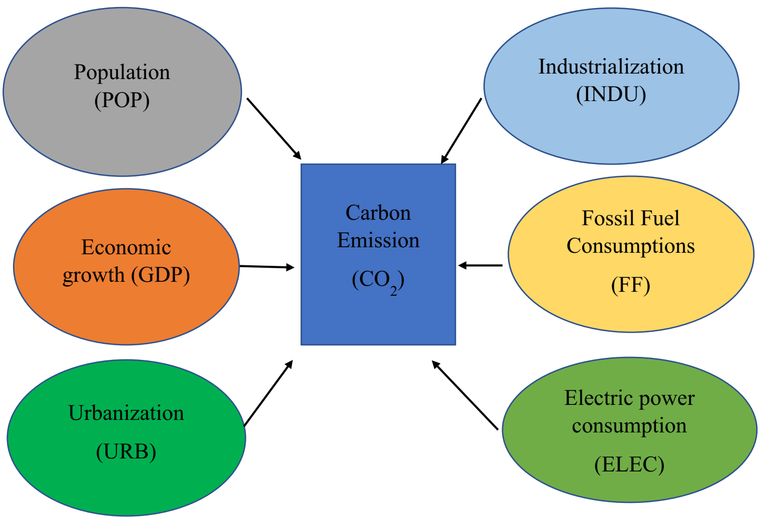

Fig. 1 Illustrate the thermotical framework

(Udemba & Keleş 2022). It provides a more nuanced analysis of social and cultural variables influencing environmental norms (Amin & Song, 2023). Its essential equation has been determined.

The formed model's equation is now represented as Eq. 1:

$$Q_{ij} = DP_{ij}^{\gamma_1} M_{ij}^{\gamma_2} N_{ij}^{\gamma_3} \omega_{ij} \tag{1}$$

where Q signifies environmental influence, P denotes population, M reflects affluence, and N symbolizes technology for country i at interval j. Constants and coefficients have been introduced with new symbols.

The logarithmic translation of the model looks like Eq. 2:

$$\ln Q_{ij} = D + \gamma_1 \ln P_{ij} + \gamma_2 \ln M_{ij} + \gamma_3 \ln N_{ij} + \omega_{ij} \tag{2}$$

we're particularly interested in CO_2 emissions as an indicative variable. Multiple recent studies have utilized similar models to understand CO_2 emission trajectories. This study innovatively employs GDP and natural resources as proxies for affluence, while technology's encompassing nature covers elements like industrialization and electrical consumption. The refined empirical expression of the research can be denoted a Eq. 3 s:

$$CO_{\{2ij\}} = g\left(POP_{\{ij\}}, GDP_{\{ij\}}, LINDU_{\{ij\}}, URB_{\{ij\}}, ELEC_{\{ij\}}\right) \tag{3}$$

The dependent variable in this expression is CO_2, which represents the amount of CO_2 emissions. Fundamental aspects of research are among the explanatory variables. POP refers to population, GDP representing income, IND refers to industrialization, URB refers to urban population in thousands and ELEC stands for electrical consumption. This new methodology takes an integrated approach to see how different socioeconomic and technological impacts might lead to differences in CO_2 emissions. This research offers an important contribution towards sustainable development and decision support system by linking commitments that are made in regard to global environmental protection by building a model that synthesizes the various relationships.

The logarithmic form of this expression can be laid out as Eq. 4:

$$\begin{aligned} LCO\_2ij = \beta\_0 + \beta\_1LPOP\_ij + \beta\_2LGDP\_ij + \beta\_3LURBA\_(\ ij) \\ + \beta\_4LINDU\_ij + \beta\_5LELEC\_ij + \omega\_ij \end{aligned} \tag{4}$$

with β_0 as the constant and β_1 to β_5 as coefficients for the respective logarithms of the variables,ω symbolizes the model's error term. It is a highly advanced understanding of the complex determinants that shape our ecological environment that is built into this unique framework, which uses data from 1972 to in adopting this new perspective, we hope it will further inspire more analyses, and offer thoughts for future policy-shaped ways towards environmental conservation.

4.3 Econometric methodology

Panel layouts are essential for ensuring the accuracy of data collection. In a 50-year study utilizing panel cointegration analysis, T significantly outweighed N. Conventional techniques such as fixed and random effect models are ineffective in this scenario considering their performance is enhanced when N is less than T. The SAARC states provide a unique context for analysis due to their shared ecological, biological, and cultural characteristics. In addition to sharing similar characteristics, these nations have signed several trade agreements. Problematic are, therefore, CSD, SH, and mixed-order stationary I(0) and I(1). Panel data diagnostics and outcomes cast additional light on these issues. Due to the extensive cooperation and coordination among SAARC nations, it has been determined that the CSD test is necessary. Even though these countries share a consistent pattern of accelerated economic growth, their relative assets are incredibly diverse. As a result, a slope homogeneity test was performed. The confirmation of CSD and SH issues is followed by the second generation's unit root and cointegration tests to validate this work further.

To address the difficulties presented by SH and CSD, this study employs the Cross-sectional design IPS or CIPS test over unit roots (Das et al., 2023a, 2023b). The cointegration test comes following the unit root test in the investigation. (Jahanger & Usman, 2023) created the panel cointegration test that considers CSD, heterogeneous impacts, and non-stationarity concerns. Figure 2 illustrates the steps of empirical techniques; it represents the conclusion of the procedures. After completing these evaluations, the investigation was conducted using the CS-ARDL method. The CSD issue is exacerbated by globalization's rise, the energy disaster, trade problems, and financial turmoil. Therefore, the CS-ARDL is intended to manage CSD, variability, and SH issues. With the adoption of second-generation CS-ARDL, the focus shifts

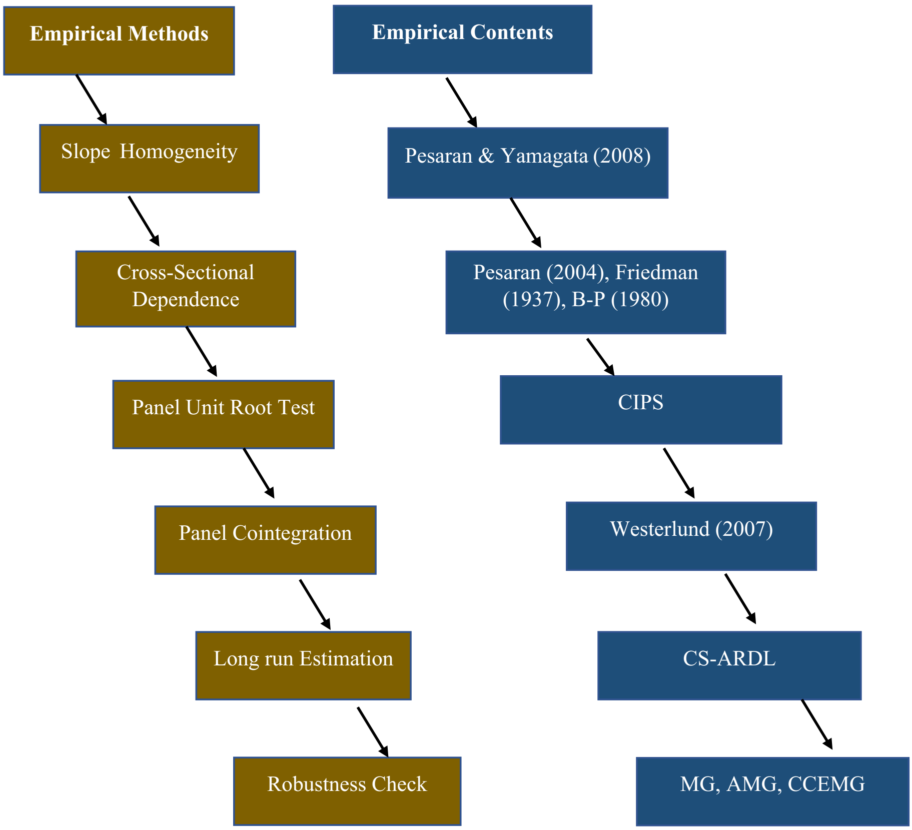

Fig. 2 Steps of empirical methods

to assuring stability. Traditional techniques can generate incorrect, insufficient, or distorted estimates in the presence of both CSD and SH. As a result, studies on the dependability of AMG, MG, and CCEMG estimation methods have been conducted. These estimators are proficient with heterogeneity and CSD and the steps are demonstrated in Fig. 2.

In particular, the analysis initially supported the hypothesis of constant gradients. The panel data were then examined for indications of CSD prior to conducting a test of panel cointegration. The study then examined the causal and determined the most precise econometric models and estimation techniques by analyzing the variable relationships. Ultimately, quality testing was conducted to confirm the authenticity of the document. The study paved the way for a comprehensive understanding and accurate interpretation of data about the economies and policies of SAARC through these extensive measures. The incorporation of multiple testing procedures revealed the complexities and distinct dynamics. Now, additional research and policy implications are possible.

4.3.1 Slope homogeneity test

The challenge of SH in panel data is similar to preparing an intricate dish in the complex field of econometrics. The 2008 test by (Shekhawat et al., 2022) analyzed that phenomenon while considering the gradients' diversity. Using Eqs. 5 and 6, determine how these flavors blend and balance. Using these formulas, one can better understand the econometric landscape by elucidating the nuances of the interaction between the various components. Each calculation imparts a distinctive character to the analysis, creating the ideal blend of art and science.

$$\Delta\hat{} = \sqrt{N}\left((S\% - k)/\sqrt{2}k\right) \times 1/N \tag{5}$$

$$\Delta_{adj} = \sqrt{N}\left((S\% - k)/\sqrt{((2k(T - k - 1))/(T + 1))}\right) \times 1/N \tag{6}$$

4.3.2 Cross-sectional dependence test

In general, panel data models presume the independence of error terms across units. Errors can exhibit correlation along cross-sectional dimensions under particular conditions. This deviation from the usual scenario, where autocorrelation or heteroscedasticity would not cause correlation, suggests that the correlation matrix is not unitary. In light of this, this study aimed to test the hypothesis that cells may operate independently. Several well-established techniques, such as the Pesaran, Friedman, and Breusch-Pagan techniques, were used to investigate the possibility of unit correlation systematically. The Pesaran CD test (Udemba & Keleş, 2022), the Pesaran scaled LM test (Xiaoman et al., 2021), the Breusch-Pagan LM test (Voumik & Sultana, 2022), and the Friedman test (Raihan, 2023b) were utilized for this evaluation. CSD issues will be identified using these methods. Using these dependable statistical methods, the study made significant strides in understanding the complicated nature of CSD. This critical factor can affect the reliability and comprehension of panel data models.

$$CSD = \frac{\sqrt{2T}}{N^2(N-1)}\left(\sum_{i=1}^{N-1}\sum_{K=i+1}^{N}\widehat{Corr}_{i,t}\right)^{\frac{1}{2}} \tag{7}$$

4.3.3 Unit root test

When SH and CSD are considered, conventional unit root tests and cointegration techniques, such as those developed by (Amin et al., 2022), frequently produce inaccurate results. (Manigandan et al., 2023) used the Cross-sectionally Augmented IPS (CIPS) test, a second-generation unit root test, to determine if relevant variables are stationary when controlling for CSD and slope heterogeneity. The below demonstrates that the essence of using a cross-sectional average when determining the CIPS cannot be overstated, thus indicating that this phenomenon is critical in enabling accurate calculation of the test statistic. In fact, recent studies indicate that the CIPS approach is gaining popularity due to its robust performance in addressing CSD and various heterogeneities. If the tested hypothesis is rejected at the first difference, then the variables are said to be stationary.

An investigation of this sort would also need the execution of a cointegration test before selecting the parameters.

$$\mathrm{CIPS} = \frac{\sum_{i=1}^{N} t_i(N, T)}{N} \tag{8}$$

he CIPS equation in yet another manner by elaborating on the function t_i and what it represents. Consider t_i (N, T) as the test statistic for the *i*-th unit in the cross-section, with *N* representing the total number of cross-sections and *T* being the time dimension.

4.3.4 Cointegration testing

This work employs a heterogeneous estimating technique to discover cointegration due to the complications of CSD, heterogeneity, and irregularity in the data. They use the approach Westerlund and Edgerton (2008) created that considers slope variance, coefficient of perseverance, and correlated errors. This work investigates the interrelationships between the pertinent variables using a second-generation panel cointegration approach. This approach successfully predicts the cointegration features when applied to cross-sectionally based heterogeneous panel data sets. It also computes error-corrected statistics to aid in panel cointegration testing.

The following mathematical expressions illustrate a common clarification of this test:

$$G_t = \frac{1}{N}\sum_{i=1}^{N} T\alpha_i \alpha_i(1) \tag{9}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N} \alpha_i SE\left(\alpha_i\right) \tag{10}$$

$$P_t = \frac{\alpha}{SE(\alpha)} \tag{11}$$

$$P_a = T\alpha \tag{12}$$

Table 3 Slope homogeneity test

Slope homogeneity tests	Δ Statistic	*P* value
Δ test	2.256**	0.035
Δadj test	2.701***	0.011

The null hypothesis is here all slope coefficients are homogeneous, ***Denotes less than 1% level. The results are continuing to indicate that the slopes are not homogeneous, as shown by the significant *p* values. This confirms the presence of varying coefficients across different countries

The null hypothesis assumes the independence of variables, while the alternative hypothesis suggests the presence of cointegration. Using these statistical constructs and tools allows a researcher to develop a subtle understanding of the associations among the studied data sets and use a refined but reliable system for testing cointegration.

4.3.5 CS-ARDL test

In the case of heterogeneity and CSD, the integration of the CS-ARDL model has indeed worked well. As such, this tool was utilized in the AMG, MG, and PMG estimator's analysis procedures. It is for this reason that the panel cointegration test is used in this study to establish that the data at hand is stationary and detect if there is any possible long-run relationship (Aamir et al., 2022). This study uses a specific CS-ARDL test developed by (Kuldasheva & Salahodjaev, 2023).This is the most costly and time-saving method compared to the dynamic and static panel personality models, MG, CCEMG, and AMG. Endogeneity, non-stationarity, mixed-order integration, SHs, and CSDs are all recognized as complicated problems. Moreover, the use of estimates that are incorrect due to improper treatment of unobserved common factors is recognized.

The following equation is utilized to represent the CS-ARDL method of CO_2 emissions levels:

$$CO_2, it = \alpha it + \sum j = 1P\beta it \cdot CO_2, i, t - j + \sum j = 0P\gamma it \cdot Xt - j + \sum j = 03\delta \cdot Yt - j + \varepsilon it \tag{13}$$

This formulation of the equation is presented in parentheses to indicate its distinct elements and make it easier to see how the individual summation terms and what they are able to contribute to the total CO_2 level. It does not change the meaning itself; rather, it conveys it somewhat differently.

$$\mathrm{Y_t} = \left(\Delta \mathrm{CO}_{2t}, \mathrm{X_t}\right)$$

$$\mathrm{X_{it}} = \left(\mathrm{LPOP_{it}}, \mathrm{LGDPpc_{it}}, \mathrm{LURBA_{it}}, \mathrm{LINDUS_{it}}, \mathrm{LFF_{it}}, \mathrm{LELEC_{it}}\right)$$

whereas:

Yt, which consists of the change in CO_2 levels, denoted by Δ CO_2 *t*, and a vector *Xt*: *Yt* = (Δ CO_2 *t*, *Xt*).

Xit, which represents various economic and demographic variables. In this particular case, *Xit* includes logarithms of population, GDP per capita, urbanization, industrialization, fossil fuel consumption, and electricity consumption.

These above equations offer further details about the components that constitute the CO_2 emission levels, including the change in CO_2 emissions and various factors like population, GDP per capita, urbanization, industry, renewable energy resources, and electricity consumption.

5 Results

5.1 Slope homogeneity test results

The results of the slope homogeneity test are shown in Table 3. The test aims to determine whether the gradients of the model's coefficients are uniform across countries. The *p* values for the and adj tests are 0.035 and 0.011, respectively. *, **, and *** indicate significance levels, with ** representing significance at the 5% level and *** at the 1% level. The results indicate that both analyses have statistically significant *p* values, contradicting the hypothesis of slope homogeneity. This suggests that the model's coefficients are inconsistent across countries, and caution is required before deriving definitive conclusions based on the coefficients.

5.2 Outcome of CSD test

Pesaran and Yamagata (2008) present a standardized form of Swamy's test for slope homogeneity in panel data models. This is even more so when the cross-section dimension (N) significantly surpasses time series dimension (T). It is known as $\tilde{\Delta}$ test and makes use of the cross-sectional variation in individual slopes, weighted by their relative precision. The same holds for (Pesaran, 2004) who invented straightforward tests of cross-section dependence in a range of panel data models, among them stationery and unit root dynamic heterogeneous panels with short T and large N. These procedures are based on average pairwise correlations between the OLS residuals from individual regressions within the panel. They can be used to analyze cross-section dependence of any fixed order p, or in the absence of a priori ordering assumption among units denoted as CD(p) and. Pesaran (2007) suggests a straightforward variation of several panel unit root tests that take account cross-section dependence. This entails the addition of cross-sectional averages from lagged levels and first differences to standard ADF regressions. Asymptotic results for both the individual cross sectionally augmented ADF (CADF) statistics and their simple averages are derived, showing that even if factor loadings vary, they have an identical asymptote.

Table 4 CSD test results

Test Statistics	*P* value
Pesaran CD test	28.589***
Pesaran scaled LM	12.387**
Friedman test	173.879*
BP LM test	77.932***

***and *show 1% and 10% significance, respectively

Table 5 Second-generation unit root test result

Variables	Level	1st Diff NT	1st Diff WT	Order
LCO_2	−1.21	−4.300***	−4.600***	I (1)
LPOP	−2.1	−3.750***	−3.900***	I (1)
LGDP	−2.040*	−2.060***	−3.030***	I (0)
LURB	−3.480*	−5.030***	−5.480***	I (0)
LIND	−2.9	−4.860***	−5.060***	I (1)
LFF	−2.010*	−3.700***	−5.650***	I (0)
LELEC	−2.350**	−4.950***	−5.250***	I (1)

P values are denoted in parentheses, and the significance levels (10, 5, and 1% respectively) are denoted by the symbols *, ** and *** the results of the second-generation unit root tests, with variables classified as I(1) and I(0) to indicate stationarity properties

Table 6 Westerlund test for cointegration results

Variables	Value	Z Value	*P* Value
Gt	−4.012	2.300	0.001
Ga	−3.342	4.478	0.988
Pt	−8.685	3.144	0.001
Pa	−2.319	4.824	0.999

The rejection of the null hypothesis for Gt and Pt variables in the cointegration tests, suggesting interdependency among long-term variables

The outcomes of tests for CSD are presented in Table 4. To detect the presence of CSD among variables, the Pesaran CD test, the Pesaran scaled LM test, the Friedman test, and the BP LM test were conducted. Asterisks are placed next to the reported *p* values to denote their significance. All tests yield statistically significant *p* values, indicating the existence of CSD in the data set. This suggests a connection between the error terms used in various countries, highlighting the necessity of considering CSD in future analysis.

5.3 Second-generation unit root test result

The results of the second-generation unit root tests for various variables are presented in Table 5. These tests aim to determine the stationarity of the variables, which is essential for subsequent analyses. The I(1) or I(0) classification indicates whether the variables are integrated in order 1 or 0. Some variables appear to be stationary at the first difference (I(1)), while others appear to be stationary at level (I(0)). These findings are crucial for accurate data modeling and interpretation.

Table 7 CS-ARDL results

Variables	Long-run results	Standard error	Short-run results	Standard error
LPOP	−6.2081	18.225	−3.1246	18.2164
LGDP	0.972	0.8261	0.235	0.8261
LURB	3.271***	0.6427	3.8765	6.6072
LIND	0.1827***	0.0615	0.1492	0.3623
LFF	−0.2753***	0.0351	−0.1996	0.3598
LELEC	−0.1897***	0.0309	−0.2113***	0.0456

CS-ARDL model, showing the significance levels of the coefficients using *, **, and *** symbols

Table 8 Long-run results

Variables	AMG	CCEMG
LPOP	−3.328 (3.094)	−4.211 (3.489)
LGDP	0.801 (1.161)	0.688 (1.322)
LURB	1.098*** (0.374)	2.751 (3.403)
LIND	0.0117*** (0.00129)	0.0632 (0.138)
LFF	−0.0359** (0.0138)	−0.0573 (0.0367)
LELEC	−0.216* (0.1024)	−0.307 (0.205)
C	22.91 (27.71)	−4.562 (51.74)

Standard errors in parentheses; ***$P<0.01$, **$P<0.05$, *$P<0.1$ the results of robustness tests using various estimation techniques. The consistency of coefficient directions across methods reaffirms the stability of findings

5.4 Westerlund test for cointegration results

The results of the Westerlund test, which evaluates the cointegration of variables, are presented in Table 6. The test determines whether or not certain variables are interdependent over time. The reported values, Z statistics, and *p* values are used to determine whether cointegration is significant. At the 1% significance level, the results indicate that the Gt and Pt variables reject the null hypothesis of no cointegration. This indicates that these variables are interdependent over the long term, highlighting the need to consider their relationships when analyzing the data.

5.5 Outcomes of CS-ARDL

Table 7 displays the outcomes of the CS-ARDL model. The coefficients and associated standard errors for both the long-run and short-run relationships between variables are presented. Asterisks denote the significance levels for coefficients. The results indicate that variables such as LURB, LIND, LFF, and LELEC have statistically significant coefficients in the long run, indicating that they substantially impact the model. Other variables, such as LPOP and LGDP, have less statistically significant coefficients, indicating the need for additional research and caution when interpreting their effects.

Table 9 Results of PMG, MG and DFE model

Variable	PMG Model				MG Model		DFE Model	
	Coefficient (Long-run)	Standard Error	Coefficient (Short-run)	Standard Error	Coefficient (Long-run)	Standard Error	Coefficient (Long-run)	Standard Error
LPOP	−0.20*	0.05	−0.05*	0.03	−0.15*	0.06	−0.18*	0.07
LGDP	0.15**	0.04	0.10**	0.02	0.20**	0.05	0.17**	0.06
LURB	0.12**	0.03	0.08**	0.01	0.10**	0.04	0.11*	0.05
LIND	0.18**	0.06	0.04**	0.02	0.22*	0.08	0.20**	0.07
LFF	−0.25**	0.07	−0.15**	0.04	−0.30**	0.09	−0.27**	0.08
LELEC	−0.10*	0.03	−0.05*	0.02	−0.08*	0.04	−0.09*	0.03

5.6 Robustness of long-run results

The consistency of the long-term results using various estimation techniques as shown in Table 8. The coefficients and standard errors for many variables are reported. Once more, asterisks denote the significance levels of coefficients. The consistency in the orientations of coefficients across various methods strengthens the reliability of the results. The results support the previous findings, such as the significance of LURB, LIND, LFF, and LELEC in the long-run model, whereas the significance of other variables varies.

The three models PMG, MG and DFE provide information on the association between socioeconomic variables and CO_2 emissions in SAARC region elaborated in Table 9. PMG findings indicate a combination of short and long-term effects on emissions, which indicated negative associations over the long term with people population in addition to fossil fuel consumption as well as positively associating GDP urbanization, and industrial development through time. This model adopts a broad scope with consideration of short-run and long-run issues, dealing also on factor effects. However, MG outcomes mirror nation-specific long-term relationships. Like in PMG, the changes recorded under MG confirm that various factors have a different effect on CO_2 emissions. This work indicates the country-specific differences between socioeconomic factors and emissions, thus allowing for a more nuanced approach suited to countries. According to DFE results, the long-term effects are homogeneous between countries. The trends adhere to PMG and MG, but the DFE model implies a generalized effect across all countries. This model offers a simplified and unvarying view, assuming equal influence in impacts across countries and may be used to generate wider perspectives. However, if deep insights on individual country-specific variations are essential MG model may be more appropriate. If we are looking for a more balanced composition of short and long-run impacts as well as refinement in understanding, then the PMG model could be recommended. This is the case when looking for a simplified, uniform impact in all countries that can be used to generate generalized observation.

The Table 10 shows results from the short run scenario, the long run scenario and a combination of both. Both LPOP and LFF have a negative correlation with CO_2 emissions in the early stage, implying immediate effects of population dynamics associated with fossil fuel usage on environmental quality.

LGDP and LURB show positive short-term effects suggesting that economic development, as well as urban population growth may temporarily raise CO_2 emissions. On

Table 10 Results for CS-ARDL with short-run restrictions, long-run restrictions and combined short-run and long-run restrictions

	Short-run restrictions		Long-run restrictions		Short-run and long-run	
Variable	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
LPOP	−1.2*	0.8	−2.5***	1.1	−1.8***	0.9
LGDP	0.5**	0.3	1.2**	0.6	0.8**	0.4
LURB	0.7**	0.4	2.0***	0.7	1.4***	0.5
LIND	0.3*	0.2	0.5**	0.3	0.4*	0.25
LFF	−0.8**	0.5	−1.5***	0.6	−1.2***	0.55
LELEC	−0.4*	0.3	−0.7**	0.4	−0.55**	0.35

the other hand, Long-term effects indicate a more negative correlation between LPOP and LFF with CO_2 emissions which indicates importance of sustainable population policies as well as energy utilization in ensuring better long term ecosystem stability. LGDP and LURB show larger positive effects over the longer term, which indicates that long-term economic growth as well as urbanization may contribute to inhibiting future emission reductions. Combining short–run and long-run limitations on effects are seemingly a mixture of both the immediate effect as well as sustainable consequences. The LFF and the LURB have uniformly good or bad effects on all models of CO_2 emissions, confirming their key positions in dynamics. All cases exhibited a notable negative relation between LFF and CO_2, which highlights the importance of energy policy in environmental sustainability. LURB leads to an increase in CO_2 emissions, and this may reflect the difficulties of managing urban environmental footprints. The varying effects of LGDP and LPOP over different timeframes indicate complicated relationships between economic growth, population dynamics, and ecological results.

6 Discussion

The worldwide recognition of environmental concerns such as pollution, changing climate, and degradation has grown recently (Amin et al., 2022). Electricity consumption has become a fundamental aspect of human existence in the modern era. Nevertheless, the question about the environmental sustainability lies in the fact that it should be able to match the growing pressure to provide other renewable sources, including solar panels. When it comes to this perspective, the SAARC nations use action plans that are in line with this objective. Shrinking the use of electricity and the leasing of the environment is both powerful ways of saving the environment. However, the current methods of electricity generations depend mostly on the use of fossil fuels, which jeopardize the natural equilibrium of our planet (Rahman et al., 2022). In the SAARC region, symmetrical solar irradiances to the same extent are much higher than those in the UK and Germany (Chien et al., 2021). One of the chances given to SAARC countries is represented by the wind power, hydropower, and renewable energy resources' incorporation for maintaining the ecological balance. In order to protect environment-based norms, there is the need to move away from fossil fuels towards use of renewable forms of energy. Population growth has a very small favorable effect on the environmental quality. Recent research focuses on critical aspects of the environmentally friendly part. Adebayo (2022) targeted the Economic Impact and Renewable Use on Ecological Footprint in MINT Nations, which emphasized renewable electricity combined with financial risks as a positive determinant of ecological sustainability. The ability to receive an education and development of various media that include the internet led to an increase in environmental awareness (Rani et al., 2022). Unlike these shifts, the growth of the GDP has promoted the industrialization process, and fast urbanization is associated with undesirable environmental influences. Economic development calls for urbanization and industrialization, but those processes go on growing beyond any limits and intensify the negative effects on the environment.

The particular concern is the unplanned urban sprawl that occurs in these SAARC nations, marked by clearance of forests, increasing number of motorized vehicles, and the construction of roadways, all leading to higher CO_2 release (H. Khan et al., 2023a, 2023b). In the same way, the rate of industrialization in the SAARC nation threatens the fragile ecosystem of the region. The landscape of SAARC countries' industries is dominated by textiles, transportation, food retail, shipbreaking, and cement production. There are needs for policies on sustainable urbanization and industrial growth to maintain appropriate balance of economic growth and environmental protection. Interestingly, the findings of our research show that the effect of economic growth on increased CO_2 emissions in SAARC countries is not significant from an econometric perspective, but it is worrying from the point of view of long-term sustainability (Sikder et al., 2022). In the case of regional economic development projects, energy resources that are not renewable are the main source of energy demand hence the need for new dynamics that focus on escalated investment both in the public and private sector in sectors that accentuate the environmental sustenance of the overall economy (Adedoyin et al., 2021). This study is very important as it provides direction to SAARC nations on how to achieve sustainability and UN SDGs. Complying with the SDGs should be accompanied by a variety of attempts including sustainability, progressing socially, and diminishing the inequalities. The study reveals that current urban trends that are associated with expansion pose a serious environmental threat that calls for a quick change on urban strategies in SAARC countries.

The investment of environmentally and socially responsible urban landscapes should be given the highest priority in the urbanization strategies of the municipalities by the prioritization of allocations to public transportation, ecological spaces, non-motorized means of movement, and emission reduction. Additionally, the impact of urbanization in commercial improvement is beneficial for the financial standing, which further helps in the gradual elimination of poverty through improved metropolitan services, such as transport networks, small enterprise developments, and access to healthcare and education. Smeltz changes in industrialization strategies in SAARC nations are also as significant owing to the detrimental consequences of industrialization on the environment.Moreover, UN-SDGS can become more attainable due to sustainable industrial development, as it may improve economic opportunities and overall quality of people's lives (Raihan, 2023a). Nevertheless, this should be done without putting the natural ecosystems at risk, creating social injustices or excluding the weaklings in the society. This balance has to be reached through the joint effort of civil society, stakeholders, and the development of efficient policies and regulations. Similarly, the generation and use of electrical power can significantly move the UN-SDGs forward along a number of fronts. Solar, wind and hydropower are among the renewable energy sources that offer cost and eco-friendliness-healthy generation of power. To achieve this, investments in renewable energy infrastructure and helping in the implementation of sustainable energy technologies are needed (Weili et al., 2022). Addressing rural availability of electricity gaps, increased funding for energy availability and the growing number of isolated and small-scale solutions can help alleviate poverty.

Adebayo and Sami Ullah (2023) examined the causal impacts of economic growth, financial development, nuclear energy, government stability, and socioeconomic conditions on the environmental quality of China, using quarterly data, covering the period 1984–2018. They found that nuclear energy, and government stability are positively causing the environmental quality, while economic growth, financial development, and socioeconomic conditions are degrading the environmental quality in China, since they are linked with increased income and energy consumption. Furthermore, all the explanatory variables are largely sensitive on different quantiles to affect the environmental quality; however, economic growth is a highly causing environmental degradation. Furthermore, Adebayo and Alola (2023) delved deeper into examining the roles of energy source efficiency, renewable energy utilization, and environment-related technologies. They found that both gas and oil efficiency promote the reduction of CO_2. Similarly, across all quantiles, environmental technological innovation and renewable energy positively promote ecological quality by mitigating CO_2. Gonzalez Zamar et al., (2020) found that sscientific production has grown annually, so the last three years have accounted for 83.23% of publications. Computer Science and Engineering remained the strongest thematic fields. Seven lines have been located in the researching evolution of smart cities based on IOT applications. Alola and Adebayo (2023b) concentrated on the emulation of the circular economy and carbon neutrality in Finland, highlighting the optimality of environmental technologies. First, they highlighted that reinvesting in resource management and green technologies had a significant contribution to environmental sustainability. Furthermore, Iceland's greenhouse gas emissions were Alola and Adebayo (2023b) topic of focus, which highlighted the importance of material utilization and circularity as ways of reducing emissions and ensuring environmental sustainability.

In the study, Hypotheses 1, 2, 4, 5, and 6 were accepted, highlighting connections between ecological footprint, land use, electricity consumption, Sustainable Development Goals, and innovative methodologies with carbon dioxide emissions. Contrarily, Hypothesis 3, proposing a link between economic growth and CO_2 emissions, was rejected, challenging conventional belief. It highlighted the novel framework utilizing a modified STIRPAT model and various statistical tests, including the CS-ARDL approach. This methodological approach aimed to enhance the reliability of the results and allowed for a multifaceted interpretation of the factors influencing CO_2 emissions in the SAARC area. The combination of innovative techniques and robust statistical analysis added depth and insight to the understanding of the complex relationship between human activities and environmental impact in the SAARC region.

7 Conclusion and policy implications

This research thus comes against the backdrop of increased global awareness of environmental challenges. It emphasizes the need for transformational initiatives in SAARC member countries to balance economic growth and environmental sustainability. The use of fossil fuels, one of the major causes of environmental pollution, is still a significant hindrance to the SDGs. Based on our analysis, the existing environmental order of the natural environment can be endangered by the current direction in which electricity production only relies on fossil fuels. The role that solar PV systems, Hydropower, wind power, and nuclear power plants would play in making SAARC successful in the quest for a sustainable future cannot be overstated. The region's capacity to utilize solar energy is notable, indicating a potential shift away from fossil fuels. The unsustainable patterns of urbanization and industrialization that exacerbate environmental issues must be resolved with caution. Intricate insights into the dynamic relationship between population growth, urbanization, industrialization, fossil fuel consumption, natural resource rent, electricity consumption, and CO_2 emissions are revealed in the conclusion of this study. By employing a comprehensive analytical framework consisting of numerous statistical analyses and the novel CS-ARDL methodology, we were able to shed light on both short- and long-term relationships, thus elucidating the impact of these factors on CO_2 emissions.

Estimates from MG, AMG, and CCEMG have validated the reliability of our findings, establishing the veracity of our conclusions. The magnitude of fossil fuel consumption emerges as a crucial factor necessitating prompt action to mitigate its effects. These strategies are consistent with the UN-SDGs and emphasize the urgency of decreasing dependence on fossil fuels and increasing the use of renewable energy sources. Our findings have far-reaching policy implications for the SAARC nations, necessitating concerted and strategic action to curb the increase in CO_2 emissions. A mission intrinsically aligned with the SDGs, abandoning fossil fuel consumption and embracing sustainable energy alternatives is central to these outcomes. To facilitate this transition, governments in the SAARC region should prioritize creating and implementing comprehensive renewable energy policies. Initiatives that incentivize and facilitate private sector investments in solar, wind, and hydroelectric power generation have the potential to generate significant CO_2 emission reductions, thus directly addressing SDG-7 demand for affordable and sustainable energy for all. In addition, our research emphasizes the central role of urbanization in the production of CO_2 emissions, which poses a direct threat to the SDGs. The policymakers of SAARC nations should create sustainable urban development strategies. Governments can effectively reduce urban emissions by promoting public transportation networks, establishing green spaces, and enforcing energy-efficient construction standards.

Financial incentives and stringent regulations to encourage the adoption of resource-efficient technologies would also help achieve SDG-9's objective of promoting sustainable industry and innovation. Given the observed industrialization trend in the SAARC region, policy interventions must prioritize environmentally sustainable industrial practices. The SDG-12 principles require governments to implement waste management regulations, incentivize the adoption of sustainable technologies, and implement taxation mechanisms to discourage the use of fossil fuels in industrial processes. These policies would foster eco-friendly industries while lowering their emissions levels. Besides regulatory actions, SAARC countries must focus on capacity-building and educational programs. Training programs that drive businesses and individuals to understand sustainability will significantly boost the goals of SDG-4, SDG-13, and so on. The achievement of SDG13, however, requires a comprehensive approach that includes widespread educational and training initiatives, which are critical in accomplishing this goal. These educational initiatives that enhance businesses' and individuals' understanding of sustainability are essential to the global fight against climate change. These initiatives might lead to a paradigm change in the environment's management through systematically evaluating current operations and introducing evidence-based practices. An awareness of the underlying dynamics of sustainability precepts facilitates the ability to make rational, proactive choices, balancing economic motives with ecological mandates.

Based on the empirical evidence, these training programs have been found to transform the mental and behavioral aspects. They reach beyond theoretical understanding; they close knowledge and practice with practicality towards the SDG target 13. Research in the future might look into the specific techniques and natural elements that contribute to the most optimal performance of these programs and ways to ensure that these programs can adapt and become useful in different fields and cultures. This objective goes beyond education as a matter of international necessity. This vision can be realized through a collaborative effort by academics, policymakers, businesses, and individuals to create a sustainable and resilient future for all. Harmonizing government, industry, and civil society actors' work will remain critical in developing robust policies and efficient implementation, supporting SDG-17 advocates for collaborative efforts. The SAARC nations can follow the policy implications of our research, which has presented a clear road map for navigating the divergent but equally important domains of environmental sustainability and economic growth. By embracing the SDGs, these countries can realize the policies that will help them find a path to an equal, environment-friendly, and prosperous future.

After a rising awareness of environmental issues worldwide, our study emphasizes the need for transformative actions in SAARC countries to balance economic development and ecological sustainability. The consumption of fossil fuels, a major enabler of environmental degradation, is an unsurpassable hurdle to achieving the SDGs. Our results show that the current trend in electricity generation based on fossil fuels threatens to destroy the fragile ecological balance. Solar photovoltaic systems, hydropower, wind power and nuclear energy cannot be overemphasized in their role of guiding SAARC towards a sustainable future. The capacity to use solar energy of the region is remarkable, which shows a possible transition from using fossil fuels. The problematic patterns of urbanization and industrialization that increase environmental problems need to be addressed with care. This study's conclusion provides complex insights into the relationship between population growth, urbanization, industrialization, fossil fuel consumption natural resource rent electricity consumption and CO_2 emissions.

Through using an integrative analytical framework that included several statistical analyses and the innovative CS-ARDL methodology, we were able to reveal not only short but also long relations thereby uncovering how these factors influenced CO_2 emissions. Our results are reliable due to the validations of MG, AMG, and CCEMG estimates. The significance of the fossil fuel consumption level becomes an important factor that requires immediate response to prevent its impacts. These approaches correspond to the UN-SDGs and underline the need for reducing reliance on fossil fuel sources as well as increasing renewable energy resources. The policy implications of our findings are wide-ranging for the SAARC nations, which require collective and strategic actions to contain CO_2 emissions. A mission inherently connected to the SDGs, leaving fossil fuel consumption for sustainable energy alternatives is at these ends. To enable this shift, appropriate renewable energy policies must be formulated and implemented by governments in the SAARC region. Incentive and facilitation programs designed to promote private sector investments in solar, wind, or hydroelectric power generation could lead to substantial CO_2 emission reduction that would directly address SDG-7 target of accessing affordable clean energy for all.

Furthermore, our study highlights the importance of urbanization in the generation process for CO_2 emissions that directly impacts on SDGs. The policymakers for SAARC countries should come up with sustainable urban development policies. Governments have the ability to successfully limit emissions in urban areas by encouraging public transport networks, establishing green spaces and enforcing energy-efficient building codes. However, the use of financial incentives and strict regulations in order to facilitate resource-efficient technology adoption would also contribute towards achieving SDG 9's goal for sustainable industry and innovation. Based on the industrialization trend that has been observed in SAARC region, policy intervention should concentrate towards promoting environmentally friendly industrial practices. The SDG-12 principles include that governments should enforce waste management regulations, encourage the adoption of sustainable technologies and impose taxation measures to prevent industry from using fossil fuels. This research, therefore, finds itself in the context of rising global awareness of the environmental pickle and is set against the backdrop of environmental challenges. It highlights the requirement for transformational initiatives in the member countries of SAARC to achieve economic growth and environmental sustainability. Fossil fuels, among the biggest causes of environmental pollution, are a significant barrier to the SGDs. From our analysis, the current trend in electricity production that depends only on fossil fuels may bring the existing environmental order of the natural environment into peril even though the role that solar PV systems, hydropower, wind power, and nuclear power plants would play in the success of SAARC in moving towards a sustainable future can be overemphasized.

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Data availability The data can be made available upon reasonable request to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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