Environmental Science and Pollution Research (2023) 30:89049–89070
https://doi.org/10.1007/s11356-023-28481-1

RESEARCH ARTICLE

Asymmetrical analysis of economic complexity and economic freedom on environment in South Asia: A NARDL approach

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Received: 14 March 2023 / Accepted: 24 June 2023 / Published online: 14 July 2023

Abstract

The environment has become a growing concern for many countries, as pollution and other environmental degradation can harm human health, economic growth, and overall well-being. This paper probes into the asymmetrical implications of economic complexity and freedom on ecological quality in four South Asian countries from 1995 to 2019. Using Nonlinear Autoregressive Distributed Lag methodology approach, our findings indicate that carbon dioxide (CO_2) emissions are intensified by economic freedom both in the long and short term, while negative and positive shocks to economic complexity increase CO_2 emissions in the long term. However, a negative economic complexity shock increases CO_2 emissions, whereas a positive shock has the opposite effect in the short run. Moreover, our results confirm the validity of the environmental Kuznets curve (EKC) hypothesis in the long run. Furthermore, we find that renewable energy usage and the interaction of FDI and renewable energy usage can help reduce environmental damage in both the short and long run. The findings suggest that countries should focus on attracting foreign direct investment that promotes the use of renewable energy. Additionally, policies aimed at encouraging renewable energy use should be implemented. It is important to note that as economic freedom and complexity increase, there is a corresponding increase in CO_2 emissions. Therefore, South Asian policy makers are advised to prioritize the reduction in fossil fuels, the promotion of energy-saving technologies and efficient production, and trade that encourages the transition of renewable energy sources to reduce CO_2 emissions.

Keywords Carbon Dioxide (CO_2) Emissions · Economic Complexity · Economic Freedom · Environmental Kuznets Curve (EKC) · Renewable Energy Use · Nonlinear Autoregressive Distributed Lag (NARDL) Model · South Asia

JEL Classification Q42 · Q54

Introduction

In recent decades, the global community has become increasingly aware of the urgent need to address human-induced environmental degradation and climate change. These pressing issues have significant implications for the Earth's ecosystem, necessitating immediate action from governments, civil societies, and key stakeholders to implement sustainable development strategies. The primary driver of climate change is the escalating concentration of greenhouse gas emissions, primarily resulting from environmental degradation (Lin and Zhu 2019). Carbon dioxide (CO_2) emissions, in particular, are the most significant greenhouse gas contributing to climate change (Ahmed et al. 2019), especially in developing nations.

For example, in 2022, climate change led to a decline in wheat and rice production by a quarter and a third in India, respectively, while Pakistan experienced 400 to 500% more rainfall than usual, posing threats to food security and energy stability. The estimated flood damage and economic losses in Pakistan alone will cost around 30 billion dollars.

Responsible Editor: Ilhan Ozturk

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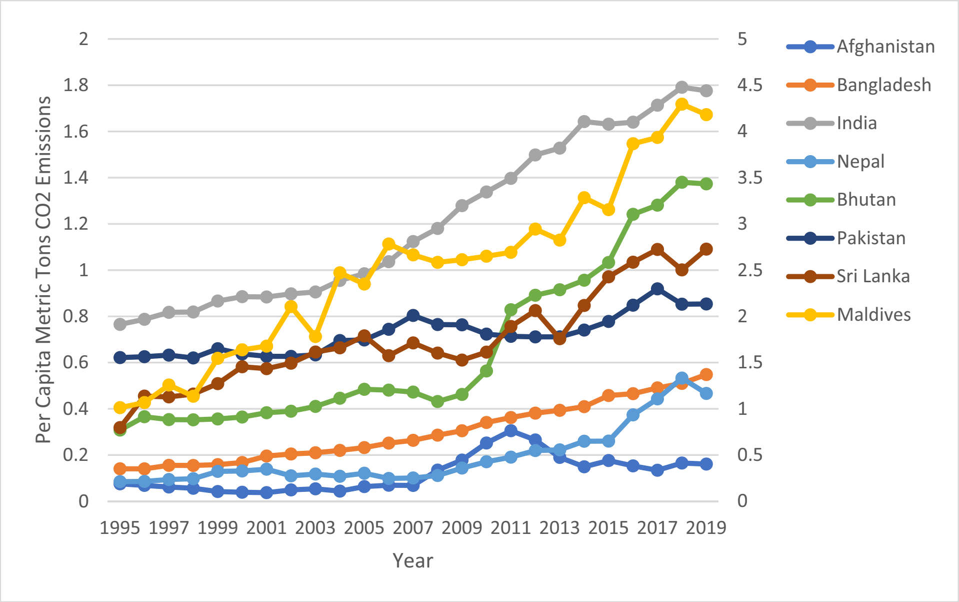

Fig. 1 Per Capita CO_2 Emissions (Metric tons) in South Asia. *Source:* World Development Indicators

Bangladesh also faced periods of drought and floods in the same year (Butt 2022; World Bank 2022).

CO_2 emissions have been on the rise in South Asian countries, particularly in the past decade. Figure 1 illustrates that India has emitted the highest tonnage of CO_2 emissions, which can be attributed to its large economy. The increase in socioeconomic activities has had profound impacts on the environment, quality of life, and economic activities due to excessive resource extraction and overuse. Environmentalists and economists alike emphasize the need for global communities to reduce CO_2 emissions, with a focus on policy measures.

The relationship between economic factors and climate change is intertwined, and both have repercussions on environmental quality and human well-being. Economic activities, driven by economic freedom, lead to increased demand, expanded manufacturing, and resource extraction. These factors contribute to environmental deterioration. Additionally, a society's knowledge level, as reflected in its exports' variety and diversification, indicates its economic complexity (Atlas 2023). Understanding the effects of economic complexity and economic freedom on the environment is crucial for promoting sustainable development.

Numerous studies have examined the effects of economic indicators such as Gross Domestic Product (GDP), urbanization, oil rents, natural resources rent, foreign direct investment (FDI), trade openness, and energy consumption on environmental quality. However, there is a lack of consensus on the direction and timeline of these indicators' effects. Some studies have established a direct association between CO_2 emissions and indicators like FDI, GDP, natural resource rent, trade openness, and urbanization, either in the long run or short run, or both (Ahmed et al. 2019; Amin and Song 2022; Anwar et al. 2022; Awosusi et al. 2022; Bekun 2019; Cheng and Hu 2022; Cui et al. 2022; Gierałtowska et al. 2022; Gnangoin et al. 2022; Grodzicki and Jankiewicz 2022; Jafri et al. 2022; Kongkuah et al. 2022; Lee et al. 2022; Mahmood et al. 2020; Ni et al. 2022; Ponce de Leon Barido and Marshall 2014; Rahman and Alam 2022; Salazar-Núñez et al. 2022; Sikder et al. 2022; Zafar et al. 2022; Zeng et al. 2022). Conversely, other studies suggest that urbanization, economic growth, FDI, trade, and natural resource rent could help reduce environmental pollution in the short- or long-term (Dada et al. 2022; Liu et al. 2023; Lv and Xu 2019; Mamkhezri et al. 2022a, b; Mehmood 2022; Otim et al. 2022; Raza et al. 2023; Zhou et al. 2022).

The impact of economic complexity and economic freedom on environmental quality has also been examined. Economic complexity has been linked to an amplified ecological footprint and increased emissions of CO_2, nitrogen dioxide, and greenhouse gases (Balsalobre-Lorente et al. 2022; Chu 2021; Peng et al. 2022). However, another study has shown that economic complexity can lead to improved ecosystems (Mehrjo et al. 2022). The relationship between economic freedom and CO_2 emissions has yielded conflicting results, with some studies suggesting a positive association and others indicating a negative one (Akadırı et al. 2021; Bjørnskov 2020; de Soysa 2021; Ghiţă, 2019; Hassan 2021; Lundström and Carlsson 2003; Majeed et al. 2021; Mamkhezri et al. 2022a, b; Rapsikevicius et al. 2021; Sart et al. 2022; Setyadharma et al. 2021a; Sheraz et al. 2021).

This research aims to investigate the asymmetrical effects of economic complexity and economic freedom on carbon emissions in South Asian countries using the Nonlinear Autoregressive Distributed Lag (NARDL) model, while controlling for other factors that influence CO_2

emissions. By considering these asymmetrical characteristics, this study adds to the existing body of knowledge. The findings of this research are expected to provide robust policy recommendations for enhancing environmental quality and stimulating sustainable economic growth, thus promoting sustainable development in the selected South Asian countries. Additionally, the results will contribute to our understanding of the factors influencing CO_2 emissions in the South Asian region and how these factors can be utilized to mitigate carbon emissions and reduce the adverse effects of climate change.

Given the ongoing discussions on sustainable development and environmental policy, this study is of utmost importance. It sheds light on a pressing and acute problem that has far-reaching implications for the long-term viability of social development, economic activities, and human welfare in South Asian countries. Furthermore, this research is crucial in the field of economic and environmental research as it underscores the necessity of adopting a comprehensive approach to mitigate climate change and its effects. This approach takes into consideration the asymmetric consequences of economic factors. More precisely, this research sheds light on the importance of balancing economic complexity and freedom with environmental concerns to ensure both economically sustainable and environmentally responsible development in the South Asian region. Undoubtedly, the outcomes of this research will provide valuable guidance for policymakers, researchers, and other stakeholders in formulating the most effective strategies to manage economic activities while minimizing their impact on the environment through the reduction of carbon emissions.

The rest of the paper is organized as follows: Sect. 2 presents a review of prior studies on the impact of economic activities on environment and theoretical background; Sect. 3 outlines the data used in this study, its sources, methodology, and econometric estimation methods; Sect. 4 covers the results and discussion; and finally, Sect. 5 concludes the study and provides policy implications for the stakeholders and limitations and directions for the future studies.

Background

The phenomenon of climate change, characterized by the gradual and persistent alteration of the earth's climate system, in conjunction with the issue of environmental degradation, denoting the deterioration of the natural environment due to human activities and other factors, represent two of the most pressing and urgent global challenges of our time that require prompt and decisive action. Many studies have been conducted to understand the relationship between economic factors and environmental outcomes, but the results have needed to be more consistent. For example, while some studies have discovered a positive relationship between economic growth and environmental pollution (Boukhelkhal 2022; Kongkuah et al. 2022; Raza et al. 2022; Salazar-Núñez et al. 2022; Thai Hung 2022; Weimin et al. 2022; Xue et al. 2022; Zafar et al. 2022), others have found a negative or insignificant relationship. Similarly, some research has suggested that using renewable energy can help reduce CO_2 emissions (Adebayo et al. 2022; Dogan and Inglesi-Lotz 2020; Habiba and Xinbang 2022; Lei et al. 2022; Musah et al. 2022; Shafiei and Salim 2014), while Zaidi et al. (2018) posited that, when looking at the individual level, carbon emissions are not considerably influenced by sustainable energy in Pakistan. This is because the primary sources of pollution in the country are natural gas and coal. The presence of these inconsistencies clearly underscores the pressing need for further research to gain a more holistic understanding of the intricate relationship that exists between economic indicators and environmental outcomes. Moreover, it is important to note that prior investigations have predominantly concentrated on the symmetrical effects of economic activities on the environment, while simultaneously falling short in the evaluation of economic freedom and economic complexity, specifically in South Asian nations. Hence, the uniqueness of this study lies in its distinctive approach towards scrutinizing the asymmetric impacts of significant economic factors, such as economic freedom and complexity, on the state of the environment.

Economic freedom is believed to be a fundamental right that allows individuals to make their own decisions about their economic activities (Heritage Foundation 2023). Academically, nations with greater economic freedom tend to have greater economic activity and growth, which may result in higher CO_2 emissions due to increased energy usage and industrial processes. Economic freedom is a concept that has been explored in economics, and various studies have analyzed its relationship with the environment through proxies such as CO_2 emissions and ecological footprint. One such study by Ghiţă (2019) found a direct and significant correlation between economic freedom and CO_2 emissions. Similarly, other studies also highlighted those countries with greater economic freedom tend to exhibit higher levels of CO_2 emissions (Hassan 2021; Karimi et al. 2022; Mehrjo et al. 2022). The reasoning behind this relationship can be attributed to the fact that economic freedom promotes economic growth and activity, leading to increased energy consumption and extraction of resources and, subsequently, higher CO_2 emissions. Oppositely, Lundström and Carlsson (2003) identified two measures of economic freedom—legal security and price stability—that lead to reduced emissions. The impact is negative for countries with low industrial GDP, but positive for those with low rates. De Soysa (2021) argued that higher economic freedom leads to lower CO_2 emissions per unit of production compared to democracy. Rapsikevicius et al. (2021) provided evidence that greater economic freedom leads to greater environmental improvement. Higher economic freedom leads to reduced CO_2 emissions and a positive impact on fishing resources. The rationale for this phenomenon can be ascribed to the reality that the presence of economic liberty encourages expansion and engagement in the market, thereby producing greater revenue that can be allocated towards eco-friendly technologies and sustainable merchandise, ultimately enhancing the ecological sustainability.

Similarly, the concept of economic complexity pertains to the generation of knowledge-based commodities of domestic origin within a specific nation, as well as the broadening of the spectrum of export commodities produced and traded by the nation, which is believed to be linked to its economic growth, development and prosperity of the nation (Sepehrdoust et al. 2019). Theoretically, countries with greater economic complexity are prone to have increased levels of CO_2 emissions might be due to a higher number of industrial processes and energy usage. The link between economic complexity and CO_2 emissions has yet to be widely researched. A limited scholarships revealed that countries with greater economic complexity generally have higher CO_2 emissions (Aluko et al. 2022; Bucher et al. 2022; Cui et al. 2022; Taghvaee et al. 2022). This connection can be explained in theory because more intricate and varied economies will likely have more industrial processes and energy consumption, resulting in higher CO_2 emissions. In contrast, Mehrjo et al. (2022) noted in their empirical research that the economic complexity has a positive influence on environmental sustainability preservation by decreasing carbon emissions, which is an essential component of the global agenda to combat climate change.

The intricate and complex nexus that exists between the rents that accrue from natural resources and the deleterious effects of environmental pollution on the ecosystem has been the subject of much scholarly discourse, which has elicited a diverse and conflicting opinions among academics and experts in the field. In theory, nations that heavily depend on natural resources for their earnings are prone to produce more CO_2 emissions because extracting and manufacturing these resources demands much energy. Several studies have examined the association between natural resource rent and CO_2 emissions, but the results have been mixed. While some studies have shown a positive relationship between the two, indicating that countries with higher natural resource rent also have higher CO_2 emissions (Awosusi et al. 2022; Bekun 2019; Dada et al. 2022; Mahmood and Saqib 2022; Onifade et al. 2023; Zhou et al. 2022). Other studies have found no significant or negative relationship between the two (Mamkhezri et al. 2022a, b; Tufail et al. 2021). The theoretical relationship between natural resource rent and CO_2 emissions is complicated and is influenced by various factors such as the type of natural resource, the level of production and extraction, and the policy environment.

Foreign direct investment (FDI) is when a foreign company or country invests in a local business or project. This could boost economic activity and growth. However, higher energy consumption and industrial processes may produce more CO_2 emissions. Several studies have examined the link between foreign direct investment (FDI) and CO_2 emissions, but the results have conflicted. Some studies have found a positive relationship between the two, indicating that FDI may increase economic activity and growth, resulting in higher CO_2 emissions (Jafri et al. 2022; Mehmet SedatUğur 2022; Rahaman et al. 2022). Other studies have found a negative or insignificant relationship between them (Mahmood 2020, 2022a; Mahmood and Furqan 2021; Saqib et al. 2023). The theoretical connection between FDI and CO_2 emissions is multifaceted and influenced by industry type and policy environment factors. For the same reason, trade is exchanging goods and services between nations. Trade can boost economic activity and development, increasing CO_2 emissions due to more energy use and industrial processes. Nevertheless, trade can also encourage the spread of technology and knowledge, aiding in curtailing CO_2 emissions. The current discourse surrounding the phenomenon of trade openness and carbon dioxide emissions has been observed to exhibit an inverted U-shaped relationship, as posited by (Mahmood 2020).

To recapitulate, the relationship between economic freedom, economic complexity, and the environment is complex. Some studies suggest that economic freedom positively correlates with environmental quality, but others suggest the opposite. This study contributes to this growing body of literature by examining the asymmetric impacts of economic freedom and economic complexity on the environment in South Asian countries. By utilizing the NARDL model, the study provides a nuanced understanding of the relationship between these factors and environmental outcomes in the region. The current study results indicate that economic freedom, while promoting economic activity, can have detrimental effects on the environment through increased resource exploitation and output. The findings suggest that both positive and negative changes in economic complexity contribute to higher carbon emissions in the long term. Specifically, a negative shock to economic complexity demonstrates statistical significance in the long term, leading to an increase in carbon emissions, whereas a positive shock results in a decline in emissions, as observed in both model 2 and model 3. Furthermore, the estimates indicate that natural resource rent (NRR) exerts a negative and significant influence on CO_2 emissions in the long term. However, the coefficients of NRR are found to be nonsignificant in the short run. The current study highlights the importance of considering the asymmetric nature of this relationship and provides valuable insights for policymakers and stakeholders dedicated to minimizing CO_2 emissions and preserving the ecosystem.

Review of literature

Urbanization, economic growth, energy consumption, and foreign direct investment have been the main topics of policy discourses as primary indicators of environmental pollution at regional and global levels. Therefore, this article's literature review is organized as follows: (i) Economic Complexity and Environment, (ii) Economic Freedom and Environment, (iii) Economic Growth and Environment, (iv) Energy Use and Environment, (v) Foreign Direct Investment and Environment, and (vi) Natural Resources Rent and Environment.

Economic complexity and environment

A society's knowledge level is measured based on the products it generates. For example, export diversification and product variety determine a country's economic complexity (Atlas 2023). Therefore, it is essential to comprehend the implications of economic complexity on the environment. Taghvaee et al. (2022) investigated how economic complexity and structure affect the environment of OECD nations. They found that a more complex economy is linked to more CO_2 emissions. In an investigation carried out by Aluko et al. (2022), an increase in the ecological footprint, as well as greenhouse gas emissions, CO_2, and nitrogen dioxide, is discovered in the presence of higher economic complexity and lower income level. However, these carbon emissions decreased when income levels increased, which supports the EKC hypothesis. Similarly, Bucher et al. (2022) point out that in the case of nations in the process of development, economic complexity could lead to a worsening of environmental troubles in the short and medium term.

Recent research studies have observed a link between CO_2 emissions and the complexity of an economy. A few studies exhibit an inverted U-shaped pattern, while others show an N-shaped pattern. These outcomes verified the EKC hypothesis in the areas studied (Balsalobre-Lorente et al. 2022; Chu 2021; He et al. 2021; Peng et al. 2022). However, Mehrjo et al. (2022) stated that economic complexity enhanced environmental sustainability by reducing carbon emissions. In contrast, Cui et al. (2022) exposed that economic complexity leads to a higher carbon footprint.

Economic freedom and environment

The increase in economic activity corresponds with the degree of economic freedom, which drives an increase in demand, resulting in heightened production and resource extraction. This combination of factors contributes to environmental degradation.

Several studies have found different conclusions about the relationship between environmental damage and economic freedom. For instance, Mamkhezri et al. (2022a, b) discovered that the tax load was the only measure of economic freedom that affected all three conservational footprints positively and significantly. According to Hassan (2021), economic freedom correlates positively with levels of carbon emissions. In addition, according to Akadırı et al. (2021), a U-shaped relation was formed by environmental damage and economic freedom; however, in the long term, this U-shaped relation is inverted. This also aligns with the hypothesis of the EKC when we talk about economic freedom in Brazil, Russia, India, China, and South Africa (BRICS). Therefore, this supports the EKC hypothesis from the point of view of economic freedom in BRICS nations. The association between the levels of CO_2 emissions and economic freedom shaped a U-type relationship. Shahnazi and Shabani (2021) found a U-type connection between the degree of CO_2 released into the air and economic freedom.

Similarly, Ghiţă (2019) discovered economic freedom's direct and significant impact on the ecological footprint. The findings of Majeed et al. (2021) documented that a rise in economic freedom positively impacts emissions in the short as well as long term. However, in the long run, there is no indirect effect, and in the short run, no effect at all is seen due to a decline in economic freedom. Therefore, economic freedom eventually exacerbates the release of CO_2 in the air by stimulating economic activity.

In contrast, Lundström and Carlsson (2003) brought two economic freedom measures into light, legal security and price stability, which are associated with decreased emissions. However, this effect is negative for nations with a relatively low percentage of GDP contributed by industry. At the same time, it is positive for countries with a relatively high rate. Similarly, de Soysa (2021) argued that higher economic freedom is associated with lower CO_2 emissions intensity per unit of production levels compared to democracy, which is associated with higher ranks.

Similarly, Uzar (2021) argued that increased institutional quality results in a smaller ecological footprint for the entire panel. Furthermore, Rapsikevicius et al. (2021) provided evidence to support the claim that greater economic freedom is associated with more significant environmental improvement. Other studies have also documented that higher economic freedom helps societies reduce CO_2

emissions (Setyadharma et al. 2021a, b; Sheraz et al. 2021). Karimi et al. (2022), however, declared that the overall economic freedom index positively impacts fishing footprints and causes an increase in fishing resource extraction.

Economic growth and environment

Economic growth is inevitable for a nation to thrive. It not only has positive effects on the economy and society but also causes the whole economy to change, including changes in sectors, populations, geography, and institutional systems (Acemoglu 2012). However, communities incur environmental harm as a cost of achieving high growth. For example, Kongkuah et al. (2022) found that the nexus of economic growth, energy use, and trade has a significant and direct effect on the release of CO_2. This implies that when the economy expands, the amount of CO_2 in the atmosphere rises, damaging the environment.

Zafar et al. (2022) revealed that the deterioration of the environment is significantly caused by economic growth. Salazar-Núñez et al. (2022) concluded that economic growth substantially influences CO_2 releases, and their findings provide evidence of EKC presence in Mexico. Boukhelkhal (2022) showed that fossil fuel (nonrenewable energy) resources and economic growth are the predominant factors leading to ecological damage in Africa. Finally, Raza et al. (2022) discovered that in some South Asian countries, there was an inverted U-shaped EKC over a long period, while CO_2 emissions were directly influenced by linear economic growth in the long term.

Similarly, Thai Hung (2022) posits that in the long and medium term, CO_2 emissions are directly impacted by economic growth and globalization in Vietnam. Weimin et al. (2022) concluded that electricity usage and economic growth boost CO_2 release in the long term. In contrast, emissions decline due to the square term of globalization and economic growth. Xue et al. (2022) pointed out an upsurge in the release of CO_2 due to uncertainty in economic policy and economic growth, while urbanization has a mitigating influence. However, the study by Ozturk and Acaravci (2010) did not detect any proof of the EKC for Turkey. Moreover, a number of studies confirmed the existence of the EKC hypothesis in the respective regions of the studies (Al-Silefanee et al. 2022; Dai et al. 2022; Khezri et al. 2022, 2023; Mahmood and Furqan 2021; Mamghaderi et al. 2023; Mamkhezri 2019; Mamkhezri et al. 2020, 2021; Mamkhezri et al. 2022a, b; Mamkhezri et al. 2022a, b; Mamkhezri et al. 2023; Mamkhezri and Khezri 2023; Murshed et al. 2022; Saqib 2022; Saqib et al. 2023; Wang et al. 2022; Yang et al. 2022a, b). According to the Mahmood (2023), the economic expansion in Latin America has resulted in some environmental impacts, and it is in the first stage of the environmental Kuznets curve. The study confirms the pollution haven hypothesis, as exports have led to an increase in CO_2 emissions in both domestic and neighboring countries. On the other hand, imports have positively impacted the surroundings of neighboring economies and the entire region of Latin America. Hence, the overall effect of trade is ecologically beneficial in Latin America. However, the study of Mahmood (2020) confirmed that the EKC exists at the second stage in North America.

Energy use and environment

The global economy and all its services and goods sectors rely heavily on energy. All the economic sectors that provide jobs, services, and products to ease and enhance residents' lives cannot function without power. In addition, the energy industry has considerable direct influence on the environment due to its status as a fundamental component of the economy. The literature has extensively investigated the ramifications of green and fossil fuel energy utilization in ecosystems. For example, Yang et al. (2022a, b) explored the relationship between carbon dioxide emissions, renewable energy, and public−private partnership investment (PPPI). The study found that the EKC is only present in the lower quantiles of carbon dioxide emissions and that renewable energy is a solution for that. The relationship is insignificant for the mid-quantiles. The study confirmed that the relationships between CO_2 emissions and PPPI are the same across all quantiles. In addition, they concluded that the use of renewable energy is helpful to mitigate the CO_2 emissions in the region. Similarly, other scholars have also revealed that the utilization of renewable energy is beneficial in reducing CO_2 emissions (Murshed et al. 2022; Saqib 2022; Saqib et al. 2023). In the same way, Musah et al. (2022) concluded that sustainable energy reduces CO_2 emissions. Other researchers have reached similar conclusions (Dogan and Inglesi-Lotz 2020; Habiba and Xinbang 2022; Shafiei and Salim 2014).

Correspondingly, Lei et al. (2022) posited that a boost in the consumption of green energy would result in a lessened release of CO_2; however, a drop in its utilization may lead to long-term pollution in China. Adebayo et al. (2022) also observed that sustainable energy could reduce the discharge of CO_2 across quantiles (0.1–0.90). Hao (2022) determined that green energy could shrink emissions in upper-middle-income nations, not poorer countries. Khattak et al. (2020) have confirmed that except for South Africa and India, the EKC hypothesis is verified in BRICS nations.

The research of Zaidi et al. (2018) concluded that at the individual level, carbon emissions are not considerably influenced by sustainable energy in Pakistan, where natural gas and coal are the primary sources of pollution. In a similar investigation, Aydoğan and Vardar (2020) found that the use of nonrenewable energy deteriorates the environment. Mehmood (2022) showed that carbon emissions declined by 13.95% due to a one percent increment in renewable energy. Subsequently, Mamkhezri et al. (2022a, b) examined the repercussions of the utilization of energy on the ecological footprints of resources, and their conclusions support the EKC hypothesis for most Asia–Pacific countries. Nonetheless, the study revealed that agricultural footprints are not affected by natural resource rents, which differs from the results of previous studies. Saqib (2022) argued that the ecological footprint of Mexico, Indonesia, Nigeria, and Turkey (MINT) nations is increasing as economic expansion leads to a rise in the usage of fossil fuels. Therefore, the use of renewable energy and implementation of environmental policies could be useful to reduce CO_2 emissions and to achieve environmental sustainability.

Foreign direct investment and the environment

Researchers have widely discussed the economic and environmental impacts of FDI. A handful of studies suggest that FDI can lead to economic growth by creating job and business opportunities, but at the same time, it also contributes to pollution. For example, Saqib et al. (2023) validated the pollution halo hypothesis that FDI and the ecological footprint are negatively correlated. Jafri et al. (2022) discovered that both direct and indirect FDI changes can positively affect CO_2 emissions, yet the positive changes have a more lasting influence. Furthermore, in India, there is support for the ‘pollution haven’ hypothesis due to FDI (Sreenu 2022). Likewise, Rahaman et al. (2022) established that in the long term, the utilization of electricity, FDI, and economic progress results in more CO_2 emissions in Bangladesh. Mahmood and Furqan (2021) argued that emissions are positively impacted by urbanization, energy use, and financial market development, but foreign direct investment has a negative impact on emissions in GCC nations.

Mehmood (2022) revealed that the conjugation of the utilization of renewable energy and FDI led to a decline in environmental pollution. Additionally, H. Mahmood (2022a, b) determined that the initial stage of the EKC is situated in Latin America, while a statistically insignificant effect of FDI on CO_2 emissions was observed. Moreover, financial market development was observed to elevate CO_2 emissions in certain South Asian countries. Furthermore, FDI was found to increase CO_2 emissions, which confirms the pollution haven hypothesis (Mehmet SedatUğur 2022). In addition, financial market development has a positive impact on carbon dioxide emissions, while foreign direct investment has a negative impact. The relationship between trade openness and carbon dioxide emissions is inverted U-shaped (Mahmood 2020). In a similar vein, Mahmood (2022a, b) argued that there are negative direct and spillover effects of FDI on consumption-based CO_2 emissions and positive spillover effects on territory-based CO_2 emissions in GCC nations.

Natural resource rent and environment

The interconnection of rents from natural resources and environmental pollution has elicited various views among academics. For example, in Colombia, Awosusi et al. (2022) observed that the revenue from such resources had a detrimental impact on the atmosphere by leading to contamination. Similarly, Ni et al. (2022) reported that rents from natural resources result in more CO_2 emissions. In addition, Onifade et al. (2023) said that using such resources had an overall destructive effect on the ecosystem, with this damage declining until the 50th quantile before increasing again.

Mahmood and Saqib (2022) conducted a study on the relationship between oil rents and CO_2 emissions in 13 OPEC member countries from 1970–2019. The findings indicate that an increase in oil rents has a positive impact on emissions in Angola, Congo, Iran, and Kuwait, while it has a negative impact in Algeria and the UAE. Conversely, a decrease in oil rents leads to an increase in CO_2 emissions in Algeria, Gabon, Nigeria, and Saudi Arabia. Similarly, Mahmood and Furqan (2021) studied the effects of oil rents and economic growth on greenhouse gas emissions in six Gulf Cooperation Council (GCC) countries. The results show a nonlinear relationship between economic growth and emissions, with an inverted U-shaped relationship, a U-shaped relationship between oil rents and nitrous oxide (N_2O) emissions and an inverted U-shaped association between oil rents and methane (CH_4) and greenhouse gas emissions (GHG).

Moreover, Bekun (2019) found that in the long term, there is a direct association between rent from natural resources and carbon emissions. Comparably, Mamkhezri et al. (2022a, b) claimed that rents from natural resources have little influence on cropland footprints. Similarly, Dada et al. (2022) and Zhou et al. (2022) found that natural resources harm the environment.

Literature gap and contribution

After examining the various studies and research papers, it is evident that there is still a gap concerning the influence of economic complexity and economic freedom on environmental quality, specifically the asymmetric impacts. More explicitly, how positive and negative changes in economic freedom and economic complexity affect the environment is unclear. To fill this knowledge gap, our study takes a fresh

Table 1 Variables Description

Variable	Notation	Measurement	Source
Carbon Dioxide Emissions	CO_2	Per Capita Metric Tons	WDI
Economic Freedom	EF	Index	Heritage Foundation
Economic Complexity	EC	Index	Harvard University
Economic Growth	GDP	Annual Growth Rate	WDI
Foreign Direct Investment	FDI	Net Inflows (Percentage of GDP)	WDI
Trade	TD	Percentage of GDP	WDI
Natural Resource Rent	NRR	Percentage of GDP	WDI
Renewable Energy Use	REU	Percentage of Total Energy Consumption	WDI

perspective on the asymmetric impacts of economic complexity and freedom on the environment. We also examine the other main economic drivers of CO_2 emissions in selected South Asian countries. This study is distinctive and addresses the gaps in the existing literature in the following manner:

1. The article discusses how asymmetrically economic freedom and economic complexity affect the environment in specific countries, which is a fresh perspective in the literature.
2. We developed three models; in the first model, we only consider economic freedom's asymmetric impacts on CO_2 emissions, controlling for other factors. In the second model, we replace economic freedom with economic complexity keeping other factors controlled. Finally, we incorporated both variables and control factors in the third model.
3. To capture the asymmetric impacts of economic complexity and economic freedom on CO_2 emissions, we utilized the NARDL model. Therefore, we believe that the findings of this study are one-of-a-kind and provide practical recommendations for improving the environment and promoting sustainable economic development in the chosen South Asian countries.

This paper contributes to the existing literature by examining how economic complexity and freedom affect environmental quality, considering asymmetric dimensions. This differs from previous research that has mainly discussed the causal or symmetric aspects of economic indicators and environmental quality. As a result, its findings are anticipated to result in robust policy recommendations for improving environmental quality and promoting sustainable economic growth, leading to sustainable development in the chosen South Asian nations. Despite the limited research in this area, the study's approach and methodology provide valuable insights into the environmental and economic field. Based on its findings, the study is expected to significantly impact policymakers and researchers interested in the ecological effects of economic indicators. It also contributes to international and regional literature on the environment and economics.

Data, model building, and methodology

This study is intended to evaluate the asymmetrical effects of economic complexity and economic freedom on the quality of the environment in four countries of South Asia, Bangladesh, India, Pakistan, and Sri Lanka, utilizing yearly data from 1995 to 2019, in addition to considering various control variables. Although efforts were made to include other South Asian nations, data limitations for certain variables prevented their inclusion. A description of the variables included in the statistical analysis is displayed in Table 1. The Heritage Foundation's economic freedom index and the economic complexity created through the HS product classification devised by Harvard University's Growth Lab are the primary variables of interest in this study.

Model building and methodology

We developed three models to empirically investigate the links between the quality of the environment, economic freedom, and economic complexity while controlling for other variables. In each model, the outcome variable is ecological quality, as evaluated by CO_2 emissions per capita. Economic freedom is the key explanatory variable in the first model (see Eq. (1)), while economic complexity is the primary variable of interest in the second model (see Eq. (2)). Finally, the third model includes both variables simultaneously, while accounting for other controlled variables (see Eq. (3)).

Following the recent literature (Awosusi et al. 2022; Habiba and Xinbang 2022; Kongkuah et al. 2022; Lei et al. 2022; Mahmood 2022a, b; Mamkhezri et al. 2022a, b; Rahman and Alam 2022; Rapsikevicius et al. 2021; and Taghvaee et al. 2022), the key factors of environmental quality include economic complexity (EC), economic freedom (EF), FDI, GDP, trade, and renewable energy use (REU). As stated above, this study has three models, and the initial forms of the models' specifications are as follows:

$$\begin{aligned} CO2_{it} = {} & \alpha_0 + \alpha_1 EF_{it} + \alpha_2 GDP_{it} + \alpha_3 GDP_{it}^2 \\ & + \alpha_4 FDI_{it} + \alpha_5 TD_{it} + \alpha_6 REU_{it} \\ & + \alpha_7 NRR_{it} + \alpha_8 FDI * REU_{it} + \mu_{it} \end{aligned} \tag{1}$$

$$\begin{aligned} CO2_{it} = {} & \beta_0 + \beta_1 EC_{it} + \beta_2 GDP_{it} + \beta_3 GDP_{it}^2 \\ & + \beta_4 FDI_{it} + \beta_5 TD_{it} + \beta_6 REU_{it} + \beta_7 NRR_{it} \\ & + \beta_8 FDI * REU_{it} + \mu_{it} \end{aligned} \tag{2}$$

$$\begin{aligned} CO2_{it} = {} & \vartheta_0 + \vartheta_1 EF_{it} + \vartheta_2 EC_{it} + \vartheta_3 GDP_{it} \\ & + \vartheta_4 GDP_{it}^2 + \vartheta_5 FDI_{it} \\ & + \vartheta_6 REU_{it} + \vartheta_7 NRR_{it} + \mu_{it} \end{aligned} \tag{3}$$

where i and t indicate cross-section (i.e., nation) and time, respectively, in each of the three model specifications. It should be noted that Eqs. (1), (2), and (3) only depict the consequences of the explanatory variables on carbon emissions over a long period. Therefore, to examine both short- and long-run implications, Eq. (1), Eq. (2), and Eq. (3) were transformed into error correction specifications, such as:

$$\begin{aligned} \Delta CO2_{it} = {} & \alpha_0 + \sum\nolimits_{k=1}^{n} \gamma_{1k} \Delta CO2_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{2k} \Delta EF_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{3k} \Delta GDP_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{4k} \Delta GDP_{it-k}^2 \\ & + \sum\nolimits_{k=0}^{n} \gamma_{5k} \Delta FDI_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{6k} \Delta TD_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{7k} \Delta REU_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{8k} \Delta NRR_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{9k} \Delta FDI * REU_{it-k} \\ & + \alpha_1 EF_{it-1} + \alpha_2 GDP_{it-1} + \alpha_3 GDP_{it-1}^2 \\ & + \alpha_4 FDI_{it-1} + \alpha_5 TD_{it-1} + \alpha_6 REU_{it-1} \\ & + \alpha_7 NRR_{it-1} + \alpha_8 FDI * REU_{it-1} + \mu_{it} \end{aligned} \tag{4}$$

$$\begin{aligned} \Delta CO2_{it} = {} & \beta_0 + \sum\nolimits_{k=1}^{n} \delta_{1k} \Delta CO2_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{2k} \Delta EC_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{3k} \Delta GDP_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{4k} \Delta GDP_{it-k}^2 \\ & + \sum\nolimits_{k=0}^{n} \delta_{5k} \Delta FDI_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{6k} \Delta TD_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{7k} \Delta REU_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{8k} \Delta NRR_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{9k} \Delta FDI * REU_{it-k} + \beta_1 EC_{it-1} \\ & + \beta_2 GDP_{it-1} + \beta_3 GDP_{it-1}^2 + \beta_4 FDI_{it-1} \\ & + \beta_5 TD_{it-1} + \beta_6 REU_{it-1} + \beta_7 NRR_{it-1} \\ & + \beta_8 FDI * REU_{it-1} + \mu_{it} \end{aligned} \tag{5}$$

$$\begin{aligned} \Delta CO2_{it} = {} & \vartheta_0 + \sum\nolimits_{k=1}^{n} \theta_{1k} \Delta CO2_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{2k} \Delta EF_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{3k} \Delta EC_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{4k} \Delta GDP_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{5k} \Delta GDP_{it-k}^2 + \sum\nolimits_{k=0}^{n} \theta_{6k} \Delta FDI_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{7k} \Delta REU_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{8k} \Delta NRR_{it-k} + \vartheta_1 EF_{it-1} \\ & + \vartheta_2 EC_{it-1} + \vartheta_3 GDP_{it-1} \\ & + \vartheta_4 GDP_{it-1}^2 + \vartheta_5 FDI_{it-1} + \vartheta_6 REU_{it-1} + \vartheta_7 NRR_{it-1} + \mu_{it} \end{aligned} \tag{6}$$

It is worth noting that Eqs. (4), (5), and (6) only reflect the symmetric outcomes of the regressors on CO_2 emissions. Following Gill et al. (2023) and Li and Sohail (2023), to analyze the asymmetrical consequences of economic complexity and freedom on the environment, we modified Eqs. (4) and (5) by taking advantage of the partial sum method as follows:

$$EC_{it}^{+} = \sum_{n=1}^{t} \Delta EC_{it}^{+} = \sum_{n=1}^{t} \max(\Delta EC_{it}^{+}, 0) \tag{7A}$$

$$EC_{it}^{-} = \sum_{n=1}^{t} \Delta EC_{it}^{-} = \sum_{n=1}^{t} \min(\Delta EC_{it}^{-}, 0) \tag{7B}$$

$$EF_{it}^{+} = \sum_{n=1}^{t} \Delta EF_{it}^{+} = \sum_{n=1}^{t} \max(\Delta EF_{it}^{+}, 0) \tag{8A}$$

$$EF_{it}^{-} = \sum_{n=1}^{t} \Delta EF_{it}^{-} = \sum_{n=1}^{t} \min(\Delta EF_{it}^{-}, 0) \tag{8B}$$

In Eqs. 7A, 7B, 8A, and 8B, EC^{+} denotes an increase in economic complexity (positive shock), and EC^{-} represents a decrease in economic complexity (negative shock). Similarly, EF^{+} denotes an increase in economic freedom, and EF^{-} represents a decrease in economic freedom. The last step is to change back to the Autoregressive Distributed Lag (ARDL) specifications (4), (5), and (6) by substituting positive and negative shocks. This results in the following:

$$\begin{aligned} \Delta CO2_{it} = {} & \alpha_0 + \sum\nolimits_{k=1}^{n} \gamma_{1k} \Delta CO2_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{2k} \Delta EF_{it-k}^{+} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{3k} \Delta EF_{it-k}^{-} + \sum\nolimits_{k=0}^{n} \gamma_{4k} \Delta GDP_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{5k} \Delta GDP_{it-k}^2 + \sum\nolimits_{k=0}^{n} \gamma_{6k} \Delta FDI_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{7k} \Delta TD_{it-k} + \sum\nolimits_{k=0}^{n} \gamma_{8k} \Delta REU_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{9k} \Delta NRR_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \gamma_{10k} \Delta FDI * REU_{it-k} + \alpha_1 EF_{it-1} \\ & + \alpha_2 GDP_{it-1} \\ & + \alpha_3 GDP_{it-1}^2 + \alpha_4 FDI_{it-1} + \alpha_5 TD_{it-1} + \alpha_6 REU_{it-1} \\ & + \alpha_7 NRR_{it-1} \\ & + \alpha_8 FDI * REU_{it-1} + \mu_{it} \end{aligned} \tag{9}$$

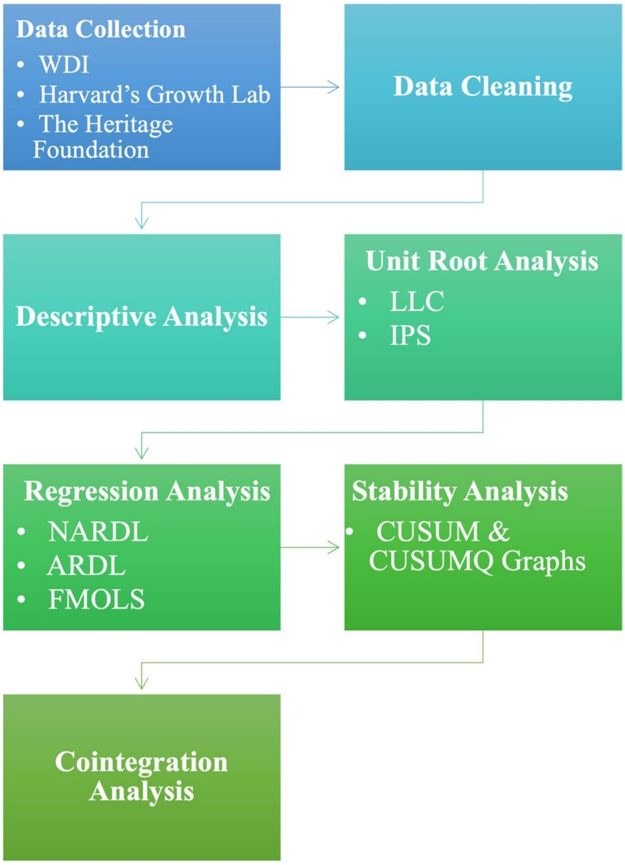

Fig. 2 Flow chart of data processing and regression analyses

Table 2 Descriptive Statistics

Variable	Obs	Mean	Std. Dev	Min	Max
$\ln CO_2$	100	-.451	.611	-1.944	.594
EF	100	3.999	.085	3.713	4.189
EC	100	4.382	.306	3.714	4.779
GDP	100	1.644	.392	0.014	2.179
GDP^2	100	3.289	.785	0.028	4.359
REU	100	3.864	.226	3.208	4.247
FDI	100	-.098	.882	-5.298	1.299
NRR	100	-.176	1.140	-2.664	1.960
TD	100	3.682	.359	3.087	4.484
FDI*REU	100	3.766	.848	-1.142	5.235

$$\begin{aligned}\Delta CO2_{it} = & \beta_0 + \sum\nolimits_{k=1}^{n} \delta_{1k} \Delta CO2_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{2k} \Delta EC^{+}_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{3k} \Delta EC^{-}_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{4k} \Delta GDP_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{5k} \Delta GDP^{2}_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{6k} \Delta FDI_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{7k} \Delta TD_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{8k} \Delta REU_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \delta_{9k} \Delta NRR_{it-k} + \sum\nolimits_{k=0}^{n} \delta_{10k} \Delta FDI * REU_{it-k} + \beta_1 EC_{it-1} \\ & + \beta_2 GDP_{it-1} + \beta_3 GDP^{2}_{it-1} + \beta_4 FDI_{it-1} \\ & + \beta_5 TD_{it-1} + \beta_6 REU_{it-1} + \beta_7 NRR_{it-1} + \beta_8 FDI * REU_{it-1} + \mu_{it}\end{aligned} \tag{10}$$

$$\begin{aligned}\Delta CO2_{it} = & \vartheta_0 + \sum\nolimits_{k=1}^{n} \theta_{1k} \Delta CO2_{it-k} + \sum\nolimits_{k=0}^{n} \vartheta_{2k} \Delta EF^{+}_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{3k} \Delta EF^{-}_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{4k} \Delta EC^{+}_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{5k} \Delta EC^{-}_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{6k} \Delta GDP_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{7k} \Delta GDP^{2}_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{8k} \Delta FDI_{it-k} + \sum\nolimits_{k=0}^{n} \theta_{9k} \Delta REU_{it-k} \\ & + \sum\nolimits_{k=0}^{n} \theta_{10k} \Delta NRR_{it-k} + \vartheta_1 EF_{it-1} + \vartheta_2 EC_{it-1} + \vartheta_3 GDP_{it-1} \\ & + \vartheta_4 GDP^{2}_{it-1} + \vartheta_5 FDI_{it-1} + \vartheta_6 REU_{it-1} + \vartheta_7 NRR_{it-1} + \mu_{it}\end{aligned} \tag{11}$$

Equations (9), (10), and (11) depict NARDL models, while Eq. (4). (5) and (6) are traditional linear ARDL models. Shin et al. (2014) show that researchers can use ordinary least squares (OLS) methodology is appropriate for both types of models for estimation and diagnostic testing. Furthermore, the use of nonlinear models allowed us to test additional assumptions in our analysis. Figure 2 provides an overview of the data processing and regression analyses conducted in this paper. To achieve the objectives of this study, data were collected from three different sources: the World Bank Development Indicators, the Heritage Foundation, and Harvard's Growth Lab. Once the data was collected, it underwent a thorough cleaning process to ensure its quality and reliability. Descriptive analysis was then performed on the selected variables. To proceed with the regression analysis, we employed Im, Pesaran, and Shin (IPS) test and Levin, Lin, and Chu (LLC) test to confirm the stationarity of the data. Once the data stationarity and no perfect multicollinearity were confirmed, we performed the NARDL model regression analysis. Additionally, a cointegration analysis was conducted to examine the long-run relationship among the factors. To assess the stability of the NARDL model, we used QSUM and QSUMQ graphical techniques, as depicted in Fig. 2.

Results and discussion

It is of utmost importance to thoroughly examine the foundational characteristics of the variables prior to commencing any regression analysis (Akhtar et al. 2023). Table 2 summarizes the descriptive statistics of the selected variables, with the average values of economic freedom and economic complexity being 3.999 and 4.382, respectively. The range of economic freedom is 3.713 to 4.189, and for economic complexity, it is 3.714 to 4.779. Similarly, the mean of CO2 emissions is -0.451, with minimum and maximum values of -1.944 and 0.594, respectively, and a standard deviation of 0.611. Furthermore, the average values of GDP and GDP2 are 1.644 and 3.289, respectively, with minimum and maximum values of 0.014 and 2.179, and 0.028 and 4.359, respectively. The standard deviation values for the former and latter variables are 0.392 and 0.785, respectively. Additionally, the average values of REU, FDI, NRR, TD, and the interaction of FDI and REU are 3.864, -0.098, -0.176, 3.682,

Table 3 Unit Root Analysis

	LLC		IPS		Integrated Order	Decision
	Intercept	Trend & Intercept	Intercept	Trend & Intercept		
$lnCO_2$	-2.796***	-2.875***	-2.899***	-2.674***	I(1)	Non-Stationary
lnEF	-4.481***	-3.078***	-5.799***	-4.349***	I(1)	Non-Stationary
lnEC	-3.857***	-2.680***	-4.195***	-2.807***	I(1)	Non-Stationary
GDP	-5.825***	-5.027***	-6.121***	-4.756***	I(1)	Non-Stationary
GDP^2	-6.064***	-5.101***	-5.860***	-4.516***	I(1)	Non-Stationary
FDI	-6.312***	-5.051***	-6.000***	-4.827***	I(1)	Non-Stationary
REU	-4.763***	-4.984***	-3.845***	-3.214***	I(1)	Non-Stationary
NRR	-8.814***	-7.646***	-7.012***	-6.330***	I(1)	Non-Stationary
TD	-2.922***	-2.155**	-3.535***	-2.594***	I(1)	Non-Stationary

*: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$

Table 4 NARDL (PMG) Regression Results

Dependent Variable: $lnCO_2$	Variable	Model (1)		Model (2)		Model (3)	
		Coefficient	t-Stat	Coefficient	t-Stat	Coefficient	t-Stat
	Long-run						
	EF_POS	0.2029***	4.968			0.2628***	8.928
	EF_NEG	0.2492***	5.978			0.2490***	6.681
	EC_POS			0.0392	1.479	0.0013	0.034
	EC_NEG			-0.0062	-0.226	0.0711**	2.353
	GDP	0.0385***	4.034	0.2756***	10.53	0.0241**	2.610
	GDP^2	-0.0038***	4.034	-0.0221***	-10.50	-0.0017**	-2.084
	FDI	0.0189	0.562	0.3571***	9.279	0.0091**	2.391
	NRR	-0.048***	-5.756	0.0242***	2.873	-0.0625***	-6.009
	REU	-0.0323***	-22.23	-0.1042***	-4.971	-0.0327***	-33.805
	TD	0.0039***	6.018	-0.0012	-0.960	0.0024***	3.248
	*FDI*REU*	-0.0004	-0.572	-0.0084***	-9.228		
	Short run						
	D (EF_POS)	0.1146	0.952			0.2031	1.387
	D (EF_NEG)	0.0164	0.131			0.0290	1.304
	D (EC_POS)			-0.053	-1.151	-0.0035	-0.043
	D (EC_NEG)			0.1691*	1.987	0.0686	1.629
	D (GDP)	-0.0297**	-2.338	-0.069*	-1.940	-0.0314**	-2.565
	$D\ (GDP^2)$	0.0026**	2.586	0.0058*	2.005	0.0025**	2.540
	D (FDI)	-0.1666***	-3.147	-0.1827**	-2.507	-0.0061*	-1.745
	D (NRR)	-0.0915	-0.949	-0.0595	1.343	-0.0823	-1.003
	D (REU)	-0.0018	-0.338	-0.0299***	-6.362	-0.0020	-0.536
	D (TD)	-0.0012	-0.710	-0.0002	-0.222	0.0005	0.384
	D (FDI*REU)	0.0032***	4.624	0.0037**	2.452		
	C	0.0425	1.542	0.0078	1.129	0.0524**	2.116
Log-likelihood		237.429		243.365		256.874	
Log-likelihood Ratio		M1 vs. M3		M1 vs. M2		M2 vs. M3	
		39.88***		11.88***		27.00***	
ECM (− 1)		-0.966*** -3.519		-0.453* -1.795		-0.802*** -3.550	

*: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$

and 3.776, respectively. Likewise, the standard deviation values for the aforementioned variables are 0.226, 0.882, 1.14, 0.359, and 0.848, respectively. To ensure the stationarity of the data, various tests were performed such as Im, Pesaran, and Shin (IPS) test and Levin, Lin, and Chu (LLC) test (see Table 3). The outcomes indicate that the data are integrated of order 1. Last, since the assessed variables did not exhibit spatial correlation, we did not pursue spatial panel models.[1]

The Pooled Mean Group (PMG) – NARDL model examines the asymmetrical ramifications of economic freedom and complexity on the quality of the environment while controlling for other factors, and the outcomes are given in Table 4. Recall, Model 1 examines economic freedom alone, while Model 2 replaces economic freedom with economic complexity. Finally, Model 3 includes economic freedom and complexity while considering other controlled variables. Our log-likelihood tests findings indicate that Model 3 best fits our data compared to models 1 and 2. Thus, the discussion of this study is based on the results of model 3. In addition, for robustness purposes, we also estimated the ARDL and Fully Modified Ordinary Least Square (FMOLS) models. Table 8 and Table 9 of the appendix summarize the outcomes of the ARDL and FMOLS analyses, respectively.

Our long-term results, summarized in Table 4, confirm that economic freedom plays a statistically significant role in the proliferation of CO_2 emissions. Specifically, a one percent increment in both negative and positive shocks to economic freedom would result in surges of 0.249% and 0.262% in CO_2 emissions, respectively. This can be attributed to economic freedom encouraging economic activities that escalate emissions, especially in developing nations where the accessibility and affordability of green energy technologies are limited, and the populace relies heavily on emission-producing sources such as fossil fuels and petroleum. However, in the short term, the impact is not statistically significant. These findings align with the conclusions of prior studies by Ghiţă (2019), Hassan (2021), Karimi et al. (2022), and Mamkhezri et al. (2022a, b) but diverge from those of Bjørnskov (2020), de Soysa (2021), Rapsikevicius et al. (2021), Sart et al. (2022), Setyadharma et al. (2021a, b), Sheraz et al. (2021), and Uzar (2021). Moreover, our conclusions from the ARDL and FMOLS analyses also confirm that economic freedom positively impacts CO_2 emissions (see Table 8 & 9 of the Appendix).

In the long term, the coefficients of economic complexity demonstrate a rise in CO_2 emissions from both positive and negative shocks. A 1% rise in positive and negative shocks to economic complexity will cause 0.0711% and 0.0013% increments in CO_2 emissions, respectively. Concerning the short-term, a 1% boost in positive shock to economic complexity causes a decline in release of CO_2 of 0.0035%, whereas a 1% increase in negative shock contributes a 0.686% increase in emissions. The long-run findings imply that with the advancement of diverse production frameworks, ecological deterioration intensifies. The augmentation of economic complexity is associated with the escalation in production and trade, which may elucidate the concomitant surge in discharges. As mastering the creation of sophisticated products with fewer resources poses a significant hurdle for developing regions such as South Asia, this outcome aligns with the fundamentals of economic complexity. Increased economic complexity leads to the production of numerous energy-demanding goods, exacerbating environmental pollution. Our findings are endorsed by the outcomes of Aluko et al. (2022), Bucher et al. (2022), Cui et al. (2022), and Taghvaee et al. (2022), and differ from those of He et al. (2021) and Mehrjo et al. (2022). Furthermore, our ARDL and FMOLS models demonstrate that economic complexity contributes to environmental harm (Table 8 & 9 of the Appendix). One reason could be the fact that the studied countries are undergoing rapid economic growth. Consequently, they may rely more heavily on energy-intensive industries such as manufacturing, transportation, and construction. This could result in higher levels of CO_2 emissions as energy consumption increases.

The outcomes of the three PMG-NARDL models exhibit a consistent pattern in the coefficients of GDP and GDP^2. There is a direct association between carbon emissions and economic growth in the long term, but the short-term correlation is negative. Conversely, GDP^2 negatively influences CO_2 emissions in the long term but positively influences CO_2 emissions in the short term. Our investigation corroborates the EKC hypothesis in the long term, aligning with the outcomes of Salazar-Núñez et al. (2022). However, carbon emissions and GDP established a U-shaped association in the short term. Moreover, the coefficients of GDP and GDP^2 are statistically significant in the short and long run in all three models. The long-term increases in CO_2 emissions are 0.0385%, 0.2756%, and 0.0241% for models (1), (2), and (3), respectively, for a 1% boost in GDP. Conversely, a 1% escalation in GDP^2 indicates a reduction in CO_2 emissions of 0.0038%, 0.0221%, and 0.0017% in models (1), (2), and (3), respectively, in the long term. Our research findings in the short-term point to a negative connection between economic expansion and carbon pollution. This could be attributed to the fact that as countries experience swift growth, they may prioritize progress over ecological issues, leading to a heightened release of carbon. Nevertheless, as countries advance and become more affluent, they may begin to place

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[1] Spatial panel models were not explored as the Moran Index values were found to be statistically nonsignificant in our study area and time period.

importance on environmental matters and put money into more eco-friendly technologies, resulting in a reduction in carbon emissions. Moreover, the ARDL models also demonstrate the presence of the EKC in the long term but not in the short run (see Table 8 of Appendix).

Moreover, our analysis indicates a long-run positive relation between FDI and carbon releases. More precisely, a 0.0091% rise in emissions is caused by every 1% increase in FDI. On the other hand, our short-term analysis suggests that FDI has a diminishing impact on carbon emissions, with a coefficient value of -0.0061%. In the short term, foreign investors may also be subject to strict environmental regulations in the host country, which they may apply to the host country. This can lead to an immediate reduction in emissions. However, in the long run, foreign investors may focus on more resource-intensive activities, such as extractive industries or large-scale manufacturing, which can increase emissions. Furthermore, as foreign firms become more established in the host country, they may prioritize profits over environmental concerns, leading to less investment in sustainable practices and increased CO_2 emissions. Additionally, the values of the coefficient of FDI are statistically significant across all three models in the short term. Therefore, to achieve sustainable development, it is important for developing countries to prioritize environmental concerns and work to ensure that foreign investment is channeled into sustainable and environmentally friendly projects. Murshed et al. (2022) have verified the findings of Khan et al. (2019); Sabir and Gorus (2019) that the influx of FDI into GDP may lead to environmental deterioration; however, this contradicts the findings of (Banerjee and Murshed 2020; Mahmood 2022a; Mahmood and Furqan 2021; Saqib et al. 2023).

The long-run coefficient of NRR revealed that a one percent increase in NRR will cause a decline in CO_2 emissions by 0.625%. In the short term, although not statistically significant, carbon emissions are negatively impacted by NRR in all three models. Natural resource rent can be used to invest in alternative industries and promote sustainable development. Moreover, NRR can also promote the adoption of renewable energy and the implementation of stronger environmental regulations. The negative association between NRR and CO_2 is supported by the literature (Karimi et al. 2022; Mamkhezri et al. 2022a, b). In contrast, Mahmood and Furqan (2021) confirmed that rents from oil resources could cause environmental degradation in Gulf Cooperation countries. This emphasizes the importance of working on both economic and environmental sustainability in the GCC region. Similarly, our findings differ from the argument that an increase in rents from natural resources increases the environmental degradation of (Mahmood and Saqib 2022). They argued that increasing oil rents can degrade the environment in some OPEC economies (Saudi Arabia, Angola, Congo, Equatorial, Guinea, Iran, Iraq, Kuwait, and Libya) by increasing CO_2 emissions; however, our outcomes aligned with their findings for Algeria, Nigeria, and the UAE that natural resource rent helps to mitigate environmental pollution.

Model 3 indicates that trade has a direct and noteworthy effect on carbon emissions in the long term. More specifically, a one percent upsurge in trade caused CO_2 emissions to soar by 0.0024% in the long term and by 0.0005% in the short run. Trade increases CO_2 emissions may be due to increased production, transport, and comparative advantage in carbon-intensive production. Moreover, the major countries of South Asia have primarily relied extensively on both domestic and foreign fossil fuels to satisfy their individual energy requirements (World Bank, 2020b). Thus, to mitigate the impact of trade on CO_2 emissions, countries can invest in sustainable production practices, renewable energy, and transportation-related emissions reduction policies. Our findings diverge from the argument that the integration of intraregional trade could help to mitigate environmental problems (Murshed et al. 2022). However, our findings are parallel to the results of (Mahmood 2020) that trade openness is responsible for environmental pollution. More specifically, our findings allied with the argument that both exports and imports have a positive influence on territory-based CO_2 emissions in GCC countries (Mahmood 2022a).

Furthermore, our estimations (Model 3) demonstrate that carbon emissions decrease by 0.0327% due to a one percent increase in REU in the long term. Similarly, the estimate is 0.002% in the short term. Moreover, the estimations of the long run also uncover that the link between carbon discharges and REU is statistically significant in the three models. The outcomes of renewable energy consumption are aligned with the findings of Murshed et al. (2022) and Yang et al. (2022a, b). Furthermore, in the long term, the interaction of FDI and REU is also helpful in mitigating environmental damage. For example, due to a 1% rise in FDI and REU, models 1 and 2 exhibit a corresponding decline in CO_2 emissions of 0.0004% and 0.0084%. Last, the FMOLS and ARDL analyses also indicate that renewable energy can help lessen environmental damage. Thus, policymakers should consider integrating FDI with the use of sustainable energy and instituting stringent environmental protocols. Governments can invigorate foreign investors to embrace eco-friendly technologies by offering rewards and simplified legal, administrative, and financial aid. This could result in a diminishing of carbon release in the long term and support the conclusions of prior investigations by Dogan and Inglesi-Lotz (2020), Habiba and Xinbang (2022), Musah et al. (2022), and Shafiei and Salim (2014).

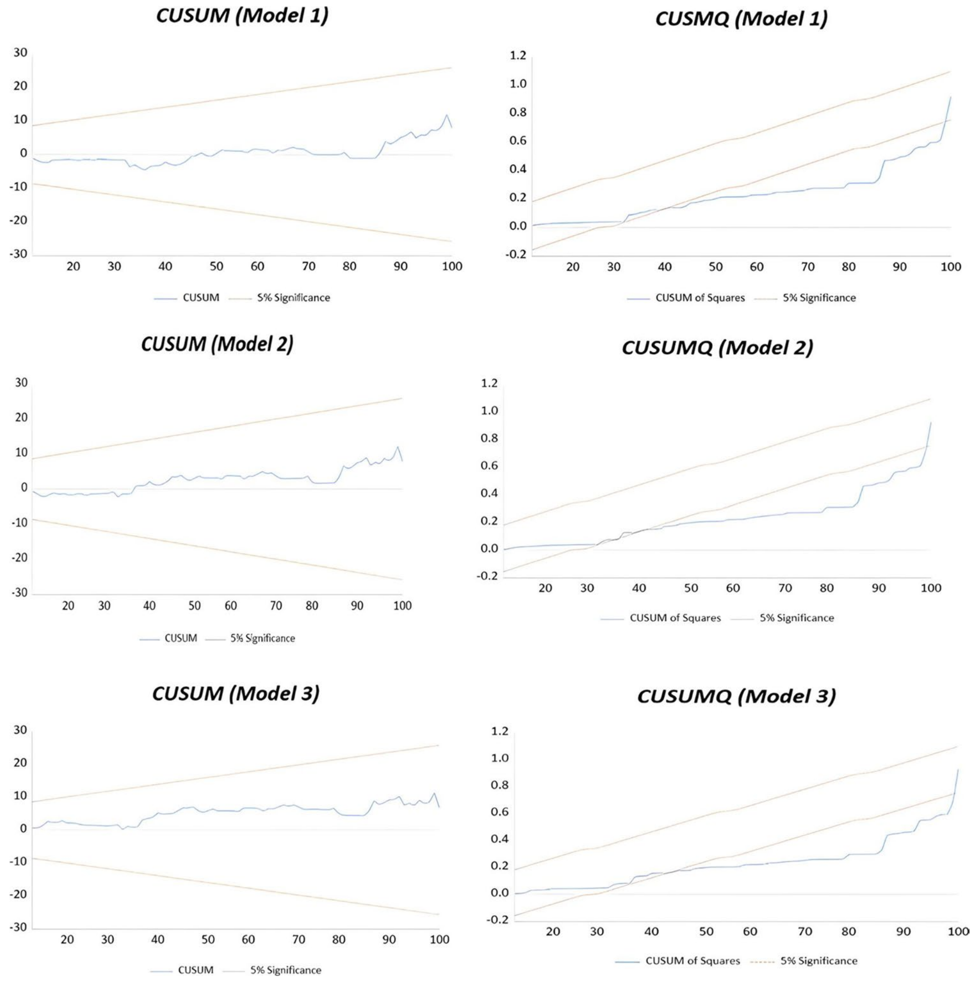

Fig. 3 CUSUM and CUSUMQ Graphs

Moreover, as depicted in Fig. 3, all models 1, 2, and 3 have been found to be parametrically stable through the CUSUM graphs.

Cointegration and asymmetrical analysis

The long run cointegration among CO_2, economic freedom, and economic complexity is tested using Kao and Pedroni tests (Table 5). The outcomes of each test indicate that all the selected variables are cointegrated in the long run. Furthermore, the cross-sectional dependency of the models examined is documented in Table 6 and confirms the cross-sectional independence across models (as observed in Table 6). Moreover, the findings of the Wald test are reported in Table 7. The results of the Wald test confirm that differences in economic freedom and negative shocks to economic complexity are statistically significant. However, the positive shock to economic complexity is not statistically significant, thus confirming the asymmetries of the variables (see Table 7).

Table 5 Outcomes of cointegration analysis

Test	Null Hypothesis	ADF t-statistics	Conclusion
Kao	No Cointegration	-5.086880***	Null hypothesis rejected
Pedroni	No Cointegration	-7.541972***	Null hypothesis rejected

*: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$

Robustness analysis

As mentioned above, we re-estimated models 1 to 3 using the FMOLS and ARDL models to check the robustness of our NARDL models findings. One of the key advantages of the FMOLS test is its ability to address issues relating to endogeneity and small sample bias (Ali et al. 2023). The ARDL and FMOLS findings are consistent with the long-term non-linear ARDL estimations, as demonstrated in Table 8 & 9 of the Appendix, suggesting the robustness of our NARDL findings.

Table 6 Cross-sectional Dependence Analysis

Null Hypothesis: Cross-sectional Independence

Test	Model 1		Model 2		Model 3	
	Statistic	Probability	Statistic	Probability	Statistic	Probability
Breusch−Pagan Chi-square	3.8952	0.6909	7.5359	0.2741	6.6256	0.3569
Pearson LM Normal	-1.7622	0.0780	-0.7113	0.4769	-0.9740	0.3300
Pearson CD Normal	0.2262	0.8210	-0.2428	0.8081	0.4781	0.6325
Friedman Chi-square	27.1846	0.2959	22.6312	0.5416	27.2795	0.2916

Conclusion

Utilizing the NARDL methodology, we assess the asymmetric implications of economic complexity and freedom on CO_2 emissions along with other economic factors such as economic growth, natural resource rent, renewable energy use, and foreign direct investment in four selected countries in South Asia (Pakistan, Bangladesh, Sri Lanka, and India) from 1995 to 2019. The investigation has provided evidence that economic freedom, while boosting economic activity, can cause harm to the environment due to increased resource exploitation and output. The findings suggest that both positive and negative changes in economic complexity produce more carbon emissions in the long term. A negative shock to economic complexity is statistically significant in the long term, whereas carbon emissions increase due to a negative shock, whereas they decline because of a positive shock in both model 2 and model 3. Additionally, estimates show that natural resource rent will negatively and significantly influence CO_2 releases in the long term; however, the coefficients of NRR are insignificant in the short run. This research contributes to providing a nuanced understanding of the relationship between economic freedom, economic complexity, and the environment and offers insights into the implications of these indicators on CO_2 emissions in South Asian countries. This study is unique in that it considers the asymmetrical consequences of these indicators in both the long and short term, providing a more comprehensive understanding of their impact on the environment. The results of this study provide valuable insights for policymakers and stakeholders as they work to reduce CO_2 emissions and protect the environment, highlight the importance of promoting renewable energy use, attracting foreign investments in the renewable energy sector, prioritizing energy-saving technologies, and promoting efficient manufacturing processes.

The findings of this investigation validate that both economic freedom and economic complexity contribute to environmental decline over a long-run period, underscoring the necessity for financial incentives from the government, such as providing interest-free or subsidized loans, to encourage the use of green production and enhance energy efficiency in the industrial and commercial sectors. In essence, there is a requirement for monetary assistance from the government to promote efficient production and manufacturing to mitigate the harmful effects of goods and services production on the region. The implementation of said policy initiatives would consequently lead to a notable decrease in CO_2 emissions within the specific geographical region, ultimately contributing to the mitigation of global warming.

In a similar vein, this study confirms the existence of the environmental Kuznets curve in the region, suggesting that if stakeholders promote green growth policies such as green industrialization and green communities, consequently, CO_2 can be reduced. Thus, to attain sustainable development and growth, the adoption of green growth policies is essential, including green urbanization and green industrialization, which should be implemented extensively. Therefore, adequate and efficient policy measures must be taken. Moreover, trade is found to be one of the CO_2 emissions producing factors, implying that stakeholders must form trade policies that are environmentally sustainable. This can be primarily attributed to the fact that the production and transportation of goods and services are responsible for environmental degradation in this region. Consequently, it is crucial for these countries to consider the association between trade policy and climate change and formulate policies that foster sustainable trade practices. More precisely, these nations need to redesign their free trade agreements with other countries (if any) and the rules and regulations of the environment when attracting investment. In addition, measures such as eco-labels, green procurement policies, sustainability standards, and environmental tariffs can be used as policy actions to mitigate the adverse impact of trade on the environment in the region.

Our results suggest that the environment's quality is significantly enhanced by employing sustainable energy sources. Energy-generated resources, such as hydropower, solar, and wind, do not emit greenhouse gases or other toxins into the atmosphere, unlike electricity generated from unsustainable energy resources, including natural gas, coal, and oil. Therefore, implementing renewable energy use can help reduce the degree of air and water pollution and the

Table 7 Wald test to investigate asymmetries

	Model 1			Model 2			Model 3		
	t-statistic	F-statistic	Chi-square	t-statistic	F-statistic	Chi-square	t-statistic	F-statistic	Chi-square
EF_POS	4.968***	24.681***	24.681***				8.929***	79.725***	79.725***
EF_NEG	5.979***	35.744***	35.744***				6.681***	44.637***	44.637***
EC_POS				1.479	2.188	2.188	0.035	0.001	0.001
EC_NEG				-2.26	0.051	0.051	2.354**	5.541**	5.541**

*: $p<0.1$; **: $p<0.05$; ***: $p<0.01$

overall carbon footprint of the energy sector. Additionally, these resources are more likely to be durable in the long run. As they do not need raw material extraction, processing, and transportation, their overall environmental effect is lower than that of nonrenewable materials. Thus, it can aid in alleviating the overall deteriorating effects of nonrenewable energy usage on the environment. Moreover, the interaction term of FDI and the use of renewable energy indicates a reduction in CO_2 discharges. FDI has the potential to support energy production efficiency and cleanliness by introducing new technologies and management practices, while renewable energy can aid in reducing carbon emissions.

Thus, following the analysis of this study, policymakers should attract renewable energy-use-led foreign investments and promote renewable energy at all levels: commercial, residential, and industrial. Promoting renewable energy use at all levels can help improve environmental quality and provide a more reliable and sustainable energy supply. Governments can encourage renewable energy use in many ways, including providing financial incentives, such as subsidies or tax credits, establishing renewable energy targets or mandates, and investing in research and development. Additionally, governments can work to remove barriers to adopting renewable energy technologies, such as streamlining the process of obtaining permits for renewable energy projects or providing technical assistance to businesses and individuals looking to transition to renewable energy sources. Moreover, the results suggest that to minimize CO_2 emissions, governments should prioritize promoting energy-saving technologies and efficient manufacturing processes. To attain the goal of sustainable environment and development, it is imperative that policymakers and governments take proactive measures to incentivize households to transition to renewable energy sources, specifically through the implementation of solar technology for lighting, heating, and cooling purposes. Furthermore, it is essential that businesses are also motivated to adopt solar technologies for these same energy needs within their corporate offices. In addition to these initiatives, governments should identify and prioritize sectors that are heavily reliant on nonrenewable energy sources such as coal and oil and mandate a certain percentage of renewable energy consumption within those sectors. In the medium term, stakeholders should explore alternative energy mixes for industries that are heavily dependent on fossil fuels but are less productive to mitigate negative environmental externalities. In the long run, policymakers and governments must encourage large-scale manufacturing and industries to embrace renewable energy sources to achieve both economic development and environmental sustainability. These measures, taken together, will not only promote energy efficiency and increase productivity but also reduce the gap between electricity demand and supply. Given the heavy reliance of this region on electricity to meet commercial, industrial, and household needs, these efforts will result in the development of prosperous and environmentally friendly communities.

This study addresses the urgent need for sustainable development and environmental policy in South Asia. By analyzing the asymmetrical effects of economic complexity and economic freedom on carbon emissions, the research provides valuable insights for policymakers, researchers, and other stakeholders. The outcomes guide the development of effective strategies to balance economic growth and environmental conservation, promoting a sustainable and resilient future for the region. One of the main limitations of this study is that it focuses on a limited sample of only four South Asian countries. To enhance the representation of all Asian nations, it is imperative to expand the sample size or undertake a comparative study encompassing the wider Asia region, including Southeast Asia, Asia–Pacific countries, among others. Furthermore, analyzing the spatial linkages could enhance the generalizability of the study's findings. Future studies should consider incorporating additional control factors, such as internal and external conflicts, infrastructure development, alternative renewable energy portfolio standards, and entrepreneurship factors, among others (Khezri et al. 2023; Mamkhezri et al. 2021). Lastly, the study primarily relied on the overall index of economic freedom and economic complexity as determinants of CO_2 emissions. Thus, a more detailed analysis that explores the impact of each sub indicator of economic freedom and economic complexity on CO_2 emissions could provide nuanced insights into property rights, tax burden, monetary freedom, and investment freedom (Mamkhezri et al. 2022a, b). In retrospection, this study offers diverse policy initiatives that can inform policymakers, scholars, and practitioners in designing effective and sustainable economic policies that balance the economic and environmental imperatives in the region.

Appendix

Please see Tables 8 and 9 here.

Table 8 ARDL Regression Outcomes

Dependent Variable: lnCO_2	Variable	(1)		(2)		(3)	
		Coefficient	t-Stat	Coefficient	t-Stat	Coefficient	t-Stat
	Long-run						
	EF	0.1424*	1.918			0.2675***	3.892
	EC			0.114**	2.052	0.1093**	2.208
	GDP	0.0156*	1.790	0.0131	1.613	0.011**	1.939
	GDP^2	-0.001	-1.132	-0.0007	-0.872	-0.0006	-1.022
	FDI	0.0369	0.803	0.0251	0.565	0.0716*	1.757
	NRR	-0.0192*	-1.691	-0.0105	-1.009	-0.0176**	-2.686
	REU	-0.0302***	-11.97	-0.0324***	-12.88	-0.0286***	-13.352
	TD	0.002**	2.383	0.0022**	2.282	0.0014*	1.835
	*FDI*REU*	-0.0005	-0.589	-0.0001	-0.189	-0.001	-1.170
	Short run						
	D (EF)	0.0556	0.366			0.0113	0.140
	D (EC)			-0.0172	-0.311	0.0214	0.295
	D (GDP)	-0.0182***	-3.179	-0.0259***	-2.879	-0.0179**	-2.187
	$D\ (GDP^2)$	0.0014***	3.637	0.0018**	2.464	0.0012	1.516
	D (FDI)	-0.1042*	-1.890	-0.1022	-1.289	-0.1439*	-1.957
	D (NRR)	-0.1052	-1.005	-0.0650	-1.109	-0.0556	-0.902
	D (REU)	-0.0017	-0.502	0.0019	0.687	0.0036	0.660
	D (TD)	-0.0007	-0.678	-0.0008	-0.967	-0.0003	-0.277
	D (FDI*REU)	0.0018**	2.221	0.0015	1.145	0.0023**	2.065
	C	0.0106	1.563	0.0091	1.398	0.0119*	1.747
Log-likelihood		227.452		231.362		239.304	
ECM (− 1)		-0.967*** -5.091		-1.004*** -7.022		-1.094*** -4.508	

*: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$

Table 9 Results of FMOLS Regression

Dependent Variable: $\ln CO_2$	Variable	(1)		(2)		(3)	
		Coefficient	t-Stat	Coefficient	t-Stat	Coefficient	t-Stat
	Long-run						
	EF	0.0692	0.718			0.0684	0.705
	EC			0.0028	0.051	0.0047	0.081
	GDP	-0.0028	-0.642	-0.0031	-0.697	-0.0028	-0.637
	GDP^2	0.0009**	2.071	0.0009**	2.083	0.0009**	2.041
	FDI	0.0184	0.571	0.0154	0.480	0.0181	0.555
	NRR	-0.0108	-1.492	-0.0106	-1.449	-0.0107	-1.464
	REU	-0.0304***	-10.43	-0.0304***	-10.40	-0.0304***	-10.345
	TD	0.0025**	2.509	0.0025**	2.457	0.0025**	2.441
	*FDI*REU*	-0.0002	-0.377	-0.0001	-0.282	0.0002	-0.358
Adj. R^2		0.528		0.525		0.521	

*: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$

Acknowledgements We sincerely thank the anonymous reviewers for their invaluable contributions and insightful comments, which have significantly enhanced the quality and depth of our work. Any remaining errors are our own.

Author contributions Conceptualization (Abdul Khaliq and Jamal Mamkhezri), Data curation (Abdul Khaliq), Formal analysis (Abdul Khaliq and Jamal Mamkhezri), Methodology (Abdul Khaliq and Jamal Mamkhezri), Resources (Jamal Mamkhezri), Software (Abdul Khaliq and Jamal Mamkhezri), Supervision (Jamal Mamkhezri), Validation (Jamal Mamkhezri), Writing—original draft (Abdul Khaliq and Jamal Mamkhezri), Writing—review and editing (Abdul Khaliq and Jamal Mamkhezri).

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability Table 1 summarizes the source of the data used. The analysis was performed in EVIEWS.

Declarations

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish All authors certify that they agree to publish this article in the Environmental Science and Pollution Research journal.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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