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Impact of globalization and industrialization on ecological footprint: do institutional quality and renewable energy matter?

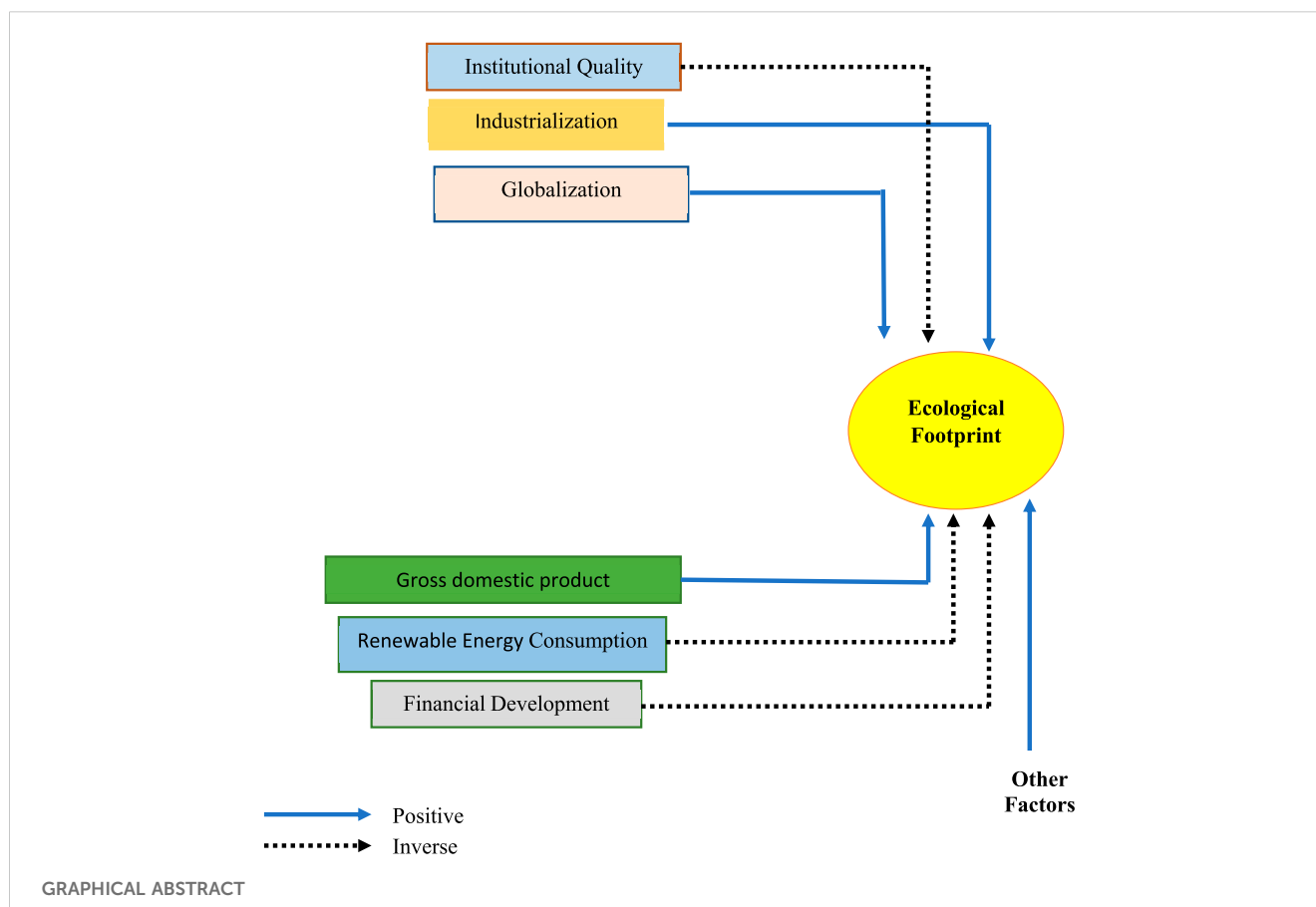
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Institutional quality (IQ) and renewable energy (RE) play crucial roles in reducing the ecological footprint (EFP), directly aligning with several United Nations Sustainable Development Goals (SDGs). IQ supports SDG-16 (Peace, Justice, and Strong Institutions) by designating effective governance, transparent policies, and legal frameworks that promote environmental sustainability. Renewable energy (RE) contributes enormously to SDG-7 (Affordable and Clean Energy) by providing sustainable, clean, and reliable energy sources that reduce dependence on fossil fuels. Adopting RE technologies also supports SDG-9 (Industry, Innovation, and Infrastructure) through investments in modern infrastructure and sustainable industrialization, fostering environmentally responsible economic growth. If institutions are strong, they ensure accountability and the implementation of regulations that facilitate the transition to RE, managing the SDG-13 (Climate Action) by actively combating climate change through policy and innovation. Therefore, the current study examines the impact of globalization and industrialization on ecological footprints (EFP) in six SAARC economies between 1996 and 2022, emphasizing the role of IQ and RE. We used the Fully Modified Ordinary Least Squares, Dynamic Ordinary Least Squares, Cross-sectional Autoregressive Distributed Lag (CS-ARDL), and panel causality approaches for the empirical study. The empirical findings demonstrate that globalization, industrialization, and GDP positively influence EFP, with coefficients of 0.82, 0.03, and 0.27. On the other hand, institutional quality, financial development, and renewable energy negatively affect EFP, with coefficients of -0.02 , -0.70 , and -0.30 . Policymakers should establish and enforce stringent regulatory frameworks to ensure environmental accountability in industrial sectors, including mandatory compliance audits, transparent reporting mechanisms, and strict penalties for violations. Also, governments in SAARC countries should introduce targeted financial incentives, such as subsidies, tax exemptions, and concessional loans, to accelerate the adoption of RE solutions and promote sustainable economic growth and environmental sustainability. Moreover, SAARC countries should strengthen institutional transparency and anti-corruption frameworks to ensure fair and effective enforcement of environmental regulations.

KEYWORDS

industrialization, institutional quality, ecological footprint, renewable energy, globalization



1 Introduction

Sustainable environmental quality has emerged as the most pressing issue in developed and developing countries over the last three decades. Also, it is on the agenda of UN sustainable development goals. Environmental sustainability is crucial for human wellbeing, primarily achieved through reducing greenhouse gas (GHG) and carbon dioxide emissions (CO₂e) (Usman et al., 2021). However, it is believed that both CO₂e and GHG emissions are a key factor in raising the overall ecological footprint (EFP), which in turn hastens the occurrence of environmental damage on a global basis (Wang et al., 2020). The EFP is widely recognized as a reliable indicator of environmental sustainability (Uddin et al., 2023c). It measures the total amount of productive land and aquatic area required to produce the resources humans consume and to manage the waste they generate (Rees et al., 1996). EFP reflects the demand placed on nature, while bio-capacity (BC) represents nature's supply. When EFP exceeds BC, it indicates an ecological deficit; when BC exceeds EFP, it signifies an ecological surplus. According to the Global Footprint Network (GFN, 2023), the world would need 1.75 Earths to meet human demands and manage waste. In 2019, the global EFP and BC per person were 2.6 gha and 1.6 gha, respectively, and by 2022, these figures were estimated at 2.6 gha and 1.5 gha, respectively (Nepal and Shrestha, 2024). More economic growth necessitates more resources, infrastructure, and energy usage, which worsens the environment and increases the release of GHG. The increase in GHG has harmed

productivity and human health. The top 25 industrialized nations were responsible for 80% of the world's emissions in 2012 (International Energy Agency (IEA), 2017). Furthermore, low-income nations are expected to contribute 80% of emissions in the future. It shows that industrialized nations have succeeded in preserving the environment and attaining long-term economic prosperity. However, emerging nations are moving differently because they devastate the environment while experiencing slow economic growth.

The primary external forces, including trade, FDI, and the elements of globalization (GLO), such as social, economic, and political, significantly influence environmental degradation (ED). Theoretically, GLO controls the direction of global investment and commerce that harms the environment. Deforestation and the demise of fisheries are two examples of how globalization depletes renewable energy (RE) sources linked to commerce. However, globalization pressures provide extensive tree plantings, green items, and technology (such as RE and hybrid autos) at lower costs and lower rent, prompting customers to embrace these products more swiftly (Copeland and Taylor, 2013). Social, economic, and political GLO are the three primary subdivisions of the phenomenon, and they are combined to create a KOF index by the Swiss Economic Institute (see Dreher, 2006). Several recent research, including (You and Lv, 2018; Khan et al., 2019; Chen et al., 2019; Saint-Akadiri et al., 2019; Azam et al., 2022b; Zaidi et al., 2019) have also used the KOF index to investigate the contribution of GLO to CO₂e. GLO surge in commerce and consumption, resource

extraction, manufacturing, and transportation impact EFP more. GLO also encourages industrial development in underdeveloped nations, where stricter environmental laws may exacerbate ecological effects. Globalization increases the demand for natural resources and hastens the worldwide deterioration of the environment. The KOF GLO index was used for 166 economies by Bu et al. (2017), who used data from 1990 to 2009 and discovered that high-level misuse of economic, political, and social globalization causes an increase in overall CO₂e. However, the impact varies between OECD and non-OECD countries. Khan and Ullah (2019) found that GLO affects the CO₂e. Saint-Akadiriri et al. (2019) found a substantial positive link between globalization and CO₂e. Farooq et al. (2022) findings reveal that globalization helps reduce environmental deterioration. Villanthenkodath and Pal (2023) found that economic GLO reduces the ecological footprint in India in the long run. They suggest that globalization can positively affect environmental sustainability in specific contexts. According to Pata et al. (2024), GLO reduces five out of seven EFP indicators in the BRICS countries, indicating a positive impact on environmental sustainability, particularly in areas like carbon and built-up land footprints. In summary, the effects of GLO on the EFP are mixed, with some countries experiencing a positive impact and others facing negative consequences, depending on local conditions and development stages.

Because of the Industrial Revolution, urbanization and industrialization (IND) have emerged as the primary avenues for social and economic development. Nevertheless, both strategies promote the rapid growth of fossil fuel use and produce significant amounts of CO₂e and other GHG. Rapid economic expansion has caused emerging nations to urbanize and industrialize quickly since the 1970s. Sharp surges in the demand for fossil fuels and CO₂ emissions also convoy these routes. IPCC (2007) reported that emissions increased from 21 to 38 Giga tons, representing a surge of roughly 80%, and made up 77% of all anthropogenic GHG emissions in 2004. Mentel et al. (2022) found that CO₂e positively impacts the GDP share of industry, whereas the production of renewable power reduces CO₂e. Governance quality factors can be very important in accomplishing sustainable environmental goals. A system of rules and principles that defend individual privileges, first-class services, and governmental regulations can be used to characterize institutions as having high institutional quality (Wu and Madni, 2021). The rule of law and corruption control are two institutional indicators that show how good an institution is. In addition to representing the competency of bureaucrats, the standard of public provision delivery, the legitimacy of government promises to programs, and the liberation of public servants from political influences, voice, and accountability also reflect the efficacy of government. Institutional strength and economic growth are mutually reinforcing, and environmental quality is tied to effective institutions that put the environment first (Singh et al., 2020). Khan A. A. et al. (2022) demonstrate that many countries' quality institutions cannot sufficiently alleviate the negative influence of every environmental aspect and environmental protection. Sheraz et al. (2022) reported that institutional quality (IQ) decreases the negative environmental externality that FD has on the environment while globalization increases it. The beneficial environmental externalities produced by human capital and RE are

increased by both globalization and institutional quality. Quito et al. (2023) reported that IND had a negative impact on the ecological footprint at the lower quantiles, meaning that it contributes more to environmental degradation in less developed or lower-income regions. However, IND had a positive impact at the upper quantiles, indicating that more advanced or developed industrialization might have a relatively lower environmental cost or potentially even some positive effects in highly developed contexts. Ullah and Lin (2024) revealed that IND was found to increase the ecological footprint, suggesting that as a country industrializes, its environmental degradation tends to rise due to higher energy consumption, emissions, and resource exploitation.

The significant role of energy in a nation's economic development cannot be ignored (Azam, 2020; Khan S. et al., 2024). Still, excessive energy use has drawbacks contributing to global warming (Murshed and Tanha, 2021). The adverse influences of global warming have become far more obvious because of a 50% surge in energy usage throughout the last two decades (Akram et al., 2020). Ulucak and Khan (2020) claim that excessive energy use has put the quality of the environment on Earth in danger. Over the past 20 years, population increase, fast economic expansion, widespread industry, and transportation have been the leading causes of rising energy demand (Espa and Holzer, 2018; Ozturk and Bilgili, 2015; Ozturk and Acaravci, 2013). Nathaniel et al. (2020) study shows that urbanization, and financial development (FD) contribute to environmental damage. Moreover, the authors added that non-renewable energy (NEC) also harms environmental deterioration, and REC does not significantly contribute to environmental quality. Lu (2020) reported that real energy consumption surges the ecological footprint. Sharma and Das (2020) claim that NEC, *per capita* income, urbanization, fertility rates, and population density are the main contributors to ED. Lei et al. (2022) discovered that a negative shock to energy efficiency has a long-term useful effect on CO₂e. Additionally, a positive shock in the use of REC has a negative significant effect on CO₂. The significant role of energy in a nation's economic development cannot be ignored (Azam, 2020). Still, excessive energy use has a drawback, contributing to global warming (Murshed and Tanha, 2021). The adverse influences of global warming have become far more obvious because of a 50% surge in energy usage throughout the last two decades (Akram et al., 2020).

In 1990, energy consumption in South Asia was relatively low, but with rising *per capita* incomes, energy demand has surged in recent years. Despite being a smaller and moderately developed country, Nepal consumes more energy than expected, with levels comparable to larger, more populous nations like India and Pakistan. Population growth in the region has further fueled economic expansion, increasing energy demands across consumer, commercial, and industrial sectors. India, contributing nearly 75% of South Asia's CO₂e. In 2012, India's annual CO₂ emissions *per capita* were 1.91 metric tons, compared to Pakistan's 0.94, Bangladesh's 0.39, Nepal's 0.14, and Sri Lanka's 0.63 metric tons (Imran et al., 2024). South Asia is among the most vulnerable regions to climate shocks, experiencing a "new climate normal" characterized by intensifying heat waves, cyclones, droughts, and floods. These climate extremes are challenging the adaptive capacity of governments, businesses, and citizens. Over the past two decades, more than half of the region's population, 750 million people across

Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka, have been affected by one or more climate-related disasters. The worsening climate conditions could severely impact the living standards of up to 800 million people in a region already home to some of the world's poorest and most at-risk populations (World Bank Group, 2024). Despite these challenges, South Asia is at the forefront of climate-smart innovations, including community-driven approaches to coastal resilience, large-scale adoption of renewable energy, and regenerative forestry practices. Accelerating and expanding these initiatives is essential to strengthening resilience against the rapidly warming climate while contributing to regional emission reductions (World Bank Group, 2024). Since the global financial crisis in 2008, South Asia has witnessed remarkable economic growth. Over the past decade, India achieved a growth rate exceeding 9%, Pakistan grew by 7%, Bangladesh and Sri Lanka by 6%, and Nepal by 4%. Strong economic growth and poverty reduction have significantly improved GDP *per capita* across South Asian countries since 2000. Energy consumption, closely linked to economic growth, reflects lifestyle trends and rising energy demand, particularly for renewable energy, which has further stimulated economic development (Imran et al., 2024). RE has significant potential in the South Asian region, with economies possessing diverse cleaner energy sources, such as wind, solar, and hydropower, which are essential for sustainable growth. However, rapid industrialization and GDP growth have contributed to the depletion of energy resources, leading to a rise in ecological footprints. To address this challenge, South Asian economies have been investing in renewable energy solutions, including wind, solar, and hydropower, to reduce their dependence on fossil fuels like oil, gas, and coal (Ma et al., 2023).

This paper investigates the impact of globalization, industrialization, IQ, and RE on EFP. Based on the above discussions, this study will test the following hypothesis:

H1: Globalization has a positive effect on the ecological footprint.

H2: Industrialization has a positive effect on the ecological footprint.

H3: There is a negative effect on institutional quality on ecological footprint.

H4: Renewable energy has a negative effect on the ecological footprint.

It examines the challenges of promoting RE, and the strategies and policies governments implement to foster its adoption and support sustainable environmental management. By analyzing the experiences of various South Asian countries, the study seeks to identify lessons and best practices that can be applied to other regions facing similar ecological challenges. For example, Pakistan has significant RE potential, such as solar and wind, while India holds the most significant RE resources in South Asia, followed by Sri Lanka and Pakistan. However, as living standards improve during later stages of GDP growth, countries focus more on RE demand, EFP reduction, and energy efficiency (Sun et al., 2023; Qing et al., 2024).

Based on the aforementioned arguments and findings, this study significantly contributes to the existing literature in five ways. Firstly,

the primary objective of this research is to investigate the collective influence of globalization, industrialization, institutional quality, and renewable energy on the ecological footprint in SAARC nations, while previous studies ignored it. By exploring these interconnected variables, the study provides a comprehensive understanding of their joint effects on environmental sustainability in the region. Secondly, this study specifically examines the relationship between globalization, financial development, and the ecological footprint within the context of SAARC nations. By focusing on this particular nexus, the research highlights the unique dynamics and challenges faced by countries in this region, contributing to a more nuanced understanding of the environmental impacts of economic globalization and financial development. Thirdly, another key contribution of this study is examining how institutional quality and renewable energy influence the ecological footprint. While prior studies have often overlooked the role of institutional quality or renewable energy, this research sheds light on how these factors can mitigate or exacerbate environmental degradation, offering valuable policy insights for the SAARC region. Fifthly, this study employs more advanced econometric techniques, such as second-generation econometrics, to address heterogeneity and cross-sectional dependency issues, which are common in panel data analyses. In contrast to earlier research that relied on traditional econometric methods, these cutting-edge techniques allow for a more robust and accurate analysis of the relationships between globalization, industrialization, institutional quality, renewable energy, and ecological footprints in the region.

The study's remaining sections are arranged as follows: Section 2 displays a literature review. Section 3 provides the data and empirical technique. Section 4 presents the findings and discussion, while Section 5 discusses the study's conclusion.

2 Literature review

2.1 Nexus between globalization and environment

Van Tran et al. (2024) examined the nexus between GLO and EFP in Indonesia from 1971 to 2019 using the Asymmetric ARDL. They found that GLO positively affects EFP. Eweade et al. (2024) used the ARDL methods from 1970 to 2015 in the United Kingdom. The results of the co-integrating regression tests and the ARDL model show that economic expansion, energy consumption, and GLO all benefit the EFP. Sabir and Gorus (2019) found that these economies' decisions to embrace globalization have worsened their environmental conditions because their EFP numbers have increased along with increased globalization activities. On the other hand, Ibrahim and Hanafy (2020) showed that GLO effectively lowered Egypt's ecological footprint levels using yearly data from 1971 to 2014. Sabir and Gorus (2019) found that GLO positively affected EFP in SAARC countries from 1975 to 2017. Ansari et al. (2021) found that GLO affects the EFP positively for the data period 1991–2016. Yilanci and Gorus (2020) observed that EFP Granger causes economic, GLO and trade MENA countries using data period 1981–2016. Farooq et al. (2022) reported that GLO aids in reducing environmental deterioration. The positive impact of

GLO is also supported by the panel quintile regression results, particularly for economies with low levels of CO₂e today. The breakdown of GLO into several categories demonstrates that this conclusion cannot be applied to all features of globalization. This study provides compelling evidence that economic GLO harms the environment's ability to maintain itself. It has been shown, however, that political globalization may be utilized to raise environmental standards. Sun et al. (2023) examined the nonlinear impacts of energy consumption and GLO on the ecological footprint in BRICS countries. Using the quantile-on-quantile approach, the study found that energy consumption had a positive effect on the EFP at most quantiles in China and India, whereas in South Africa, the effect was negative at most quantiles. GLO positively influenced the ecological footprint at most quantiles in China and South Africa, while Brazil, India, and Russia experienced a negative impact at most quantiles. Villanthenkodath and Pal (2023) investigated the impact of economic GLO on the ecological footprint in India from 1990 to 2018, while also considering economic growth and energy consumption. Employing the autoregressive distributed lag (ARDL) approach and dynamic ARDL simulation, the study confirmed a long-run relationship among the variables. The findings revealed that economic globalization and energy consumption reduce the ecological footprint in the long run, whereas economic growth increases it. Pata et al. (2024) analyzed the effects of income, GLO, and technological innovation on the ecological footprint and its subcomponents in BRICS countries for the period 1992–2020. Using the panel LM cointegration test and the common correlated effects estimator, the study found that economic growth increases the EFP, while globalization reduces five out of the seven ecological footprint indicators. Technological innovation, however, was found to have no significant impact on the EFP indicators.

2.2 Nexus between industrialization and environment

According to Li and Lin (2015), industrialization was linked to higher energy demand and modified energy consumption patterns in the infancy of economic growth, which caused higher CO₂e. Mentel et al. (2022) discovered that the industry's GDP share significantly impacts CO₂e, whereas CO₂e are reduced by the production of REC in Sub-Saharan Africa. Azam et al. (2022a) studied the nexus between IND and CO₂e from OPEC economies. They observed that environmental pollution is increased by urbanization, industrialization, and energy usage in six OPEC countries for the data period 1971–2018. Quito et al. (2023) analyzed the global impacts of industrialization, RE, urbanization, and foreign direct investment (FDI) on the ecological footprint over the period 1995–2017. Using Westerlund cointegration and quantile regression techniques. The findings revealed that economic development increased environmental degradation across all quantiles globally, whereas urbanization and renewable energy reduced degradation, with the most significant effects observed in the upper quantiles. Industrialization negatively impacted the lower quantiles but had a positive impact on the upper quantiles. Additionally, FDI inflows were found to have a detrimental effect at the 40th, 50th, 60th, and 80th quantiles, supporting the pollution

haven or halo hypothesis (PHH). The study emphasized the need for sustainable economic growth processes, stricter environmental laws for FDI inflows, and sustainable urbanization and industrialization policies. Ullah and Lin (2024) investigated the relationships between financial structure, industrialization, urbanization, export diversification, and the ecological footprint in Pakistan from 1985 to 2022. By employing the dynamic autoregressive distributed lag (DARDL) approach, the study revealed that financial structure followed an inverted U-shaped pattern in relation to the ecological footprint, indicating that an effective financial structure reduces environmental degradation. The results also showed that industrialization and urbanization increased the ecological footprint, while export diversification decreased it. The study concluded that the government should promote sustainable development by encouraging eco-friendly technologies, optimizing financial resource allocation, and enhancing the financial system's role in supporting environmentally sustainable growth.

2.3 Nexus between financial development and environment

Ashraf et al. (2022) analyzed the nexus between financial development (FD) and EFP in a worldwide sample of 124 economies using the two-step GMM. They found that FD has an inverted-U-shaped relationship with the EFP, permitting the initially detrimental effect on the environment to revert to beneficial effects. In their study, Tamazian et al. (2009) found that the Kuznets environmental assumption is still in place in the BRICS nations. Their results imply that financial openness and liberalization are the key drivers of CO₂ reduction. According to their study, measures promoting economic openness and liberalization to draw more FDI for research and development might lessen ED in the nations under consideration. Another study by Tamazian and Rao (2010) found that economic liberalization plays a key role in ED, while there is a lack of excellent institutional efficiency. Khalid et al. (2021) examined the determinants of environmental quality for the SAARC region for data period 1990–2017. Compared to a group of SAARC nations, Bangladesh and Sri Lanka show a much higher pollution level as a result of financial growth, according to country-specific statistics. However, it enhances Nepal's environmental quality. Baloch et al. (2019) indicate that financial growth favors EFP, which suggests that financial development causes a rise in EFP in BRI nations. Aslam et al. (2023) examined the impact of FD on the ecological footprint in 43 middle-income and 45 high-income countries over the period 1990–2020. Using panel quantile regression to address data outliers and non-normality, the study found an inverted U-shaped relationship between financial development and ecological footprint in the 25th and 50th quantiles, indicating that advanced financial development reduces ecological footprint. Furthermore, countries such as China, Australia, Denmark, Italy, Germany, Japan, France, South Korea, Netherlands, Luxembourg, Singapore, Switzerland, Spain, the United Kingdom, and the United States have achieved higher financial development, which has begun to lower their ecological footprint. Industrialization was found to increase the

ecological footprint, while urbanization and export diversification exhibited mixed effects across countries and quantiles. The study recommends that other countries improve their financial sectors to reduce their ecological footprint. [Saqib et al. \(2024\)](#) analyzed the effects of environmental innovations, financial development, green growth, and energy use on the ecological footprint in the ten countries with the highest ecological footprints from 1990 to 2019. Using a panel causality approach, the study found that environmental innovations, green growth, and renewable energy positively impact the ecological footprint, while financial development and non-renewable energy use exacerbate environmental degradation. The results demonstrated bidirectional causality between environmental innovations, green growth, renewable and non-renewable energy, and the ecological footprint, while a unidirectional causal relationship was observed from financial development to ecological footprint and green growth.

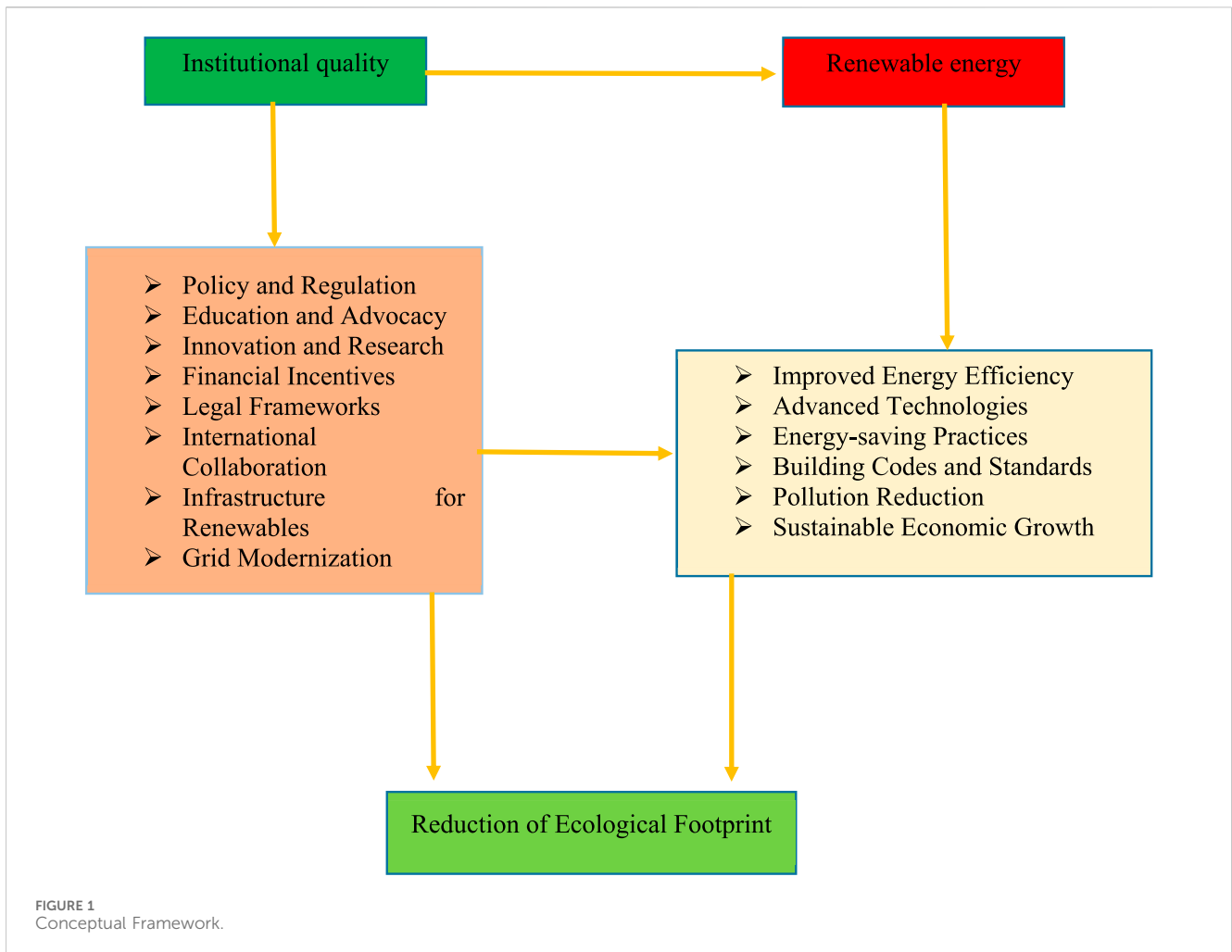
2.4 Nexus between institutional quality and environment

[Azimi and Rahman \(2023\)](#) examined the nexus between institutional quality (IQ) and EFP in G20 economies. They found that IQ reduced the EFP. The empirical results of [Obobisa et al. \(2022\)](#) show that the use of REC and green technology has a considerable negative influence on CO₂e. On the other hand, CO₂e is positively impacted by the IQ, the use of fossil energy and economic expansion in African nations. [Khan H. et al. \(2022\)](#) observed that many nations' quality institutions are now unable to sufficiently reduce each environmental factor's harmful effects and preserve the environment 2002–2019. [Sheraz et al. \(2022\)](#) study results show that institutional quality decreases the negative environmental externality that FD has on the environment while globalization increases it in BRI economies. The useful environmental externalities produced by human capital and REC are increased by both globalization and institutional quality. [Azimi and Rahman \(2023\)](#) investigated the impact of IQ on the EFP in G20 countries during the period 2000–2022. The results revealed that IQI significantly reduces EFP, with the transparency index showing the highest impact. Additionally, IQI was found to effectively moderate the relationships between EFP, financial development, human development, economic growth, and energy consumption, while being insignificant in reducing the negative effects of globalization. [Dam et al. \(2024\)](#) analyzed the role of green growth and IQ on environmental sustainability by examining CO₂ emissions, ecological footprint, and the inverted load capacity factor in OECD countries. Employing three separate models, the study found that green growth significantly reduces CO₂e, EFP, and inverted load capacity factor in the long run, with reductions of 0.563%, 0.373%, and 0.198%, respectively, for a 1% increase in green growth. Institutional quality was shown to have a significant positive impact on environmental degradation in the long run, while population effects on sustainability were found to be significant but mixed. [Addai et al. \(2024\)](#) examined the dynamic relationship between RE, IQ, and ecological footprint in the Next 11 countries from 1990 to 2022. Using the cross-

sectionally augmented autoregressive distributed lag (CS-ARDL) method, the study demonstrated that renewable energy reduces the ecological footprint, provided institutional quality positively influences pro-environmental outcomes. The results highlighted that while economic growth often exacerbates environmental degradation, improved institutional quality and increased investment in renewable energy can help achieve environmental sustainability goals.

2.5 Nexus between renewable energy and environment

Using the multiple threshold model, [Li et al. \(2022\)](#) analyzed the connection between RE and EFP in 120 global countries from 1995 to 2014. They found that NRE has a negative effect on EFP while RE has a positive effect on EFP. [Sahoo and Sethi \(2021\)](#) found feedback links between the EFP and economic development, GLO, and natural resource availability in developing nations from 1990 to 2016. The findings of [Nathaniel and Khan \(2020\)](#) imply that urbanization, economic expansion, and FD all contributed to environmental deterioration in the MENA region during 1990–2016. Further, non-renewable energy (NEC) significantly worsens the environment, while RE does not considerably influence environmental quality. [Lu \(2020\)](#) reported that real income, energy consumption and trade openness are have positive effect on EFP in 13 Asian economies between 1973 – 2014. [Sharma et al. \(2020\)](#) indicated that NEC, *per capita* income, and population density were the main causes of ED in South Asia from 1990 to 2015. The empirical findings of [Dogan et al. \(2020\)](#) show the significance of energy intensity and energy structure as key factors in ED for BRICS economies during 1980 – 2014. [Lei et al. \(2022\)](#) found that a negative shock to energy efficiency has a long-term beneficial effect on CO₂e. Moreover, positive shock in the use of REC has a negative significant effect on CO₂e, but negative shock in the use of REC results in an increase in pollutant emissions over time. A positive shock to using REC and energy efficiency has a short-term, beneficial negative impact on CO₂e. [Appiah et al. \(2023\)](#) examined the effectiveness of environmental policy, RE, and innovation on reducing the EFP in 29 OECD countries from 1990 to 2020. Using the CS ARDL methods. The study found that environmental policy, innovations and RE significantly reduces EFP. However, population density and industrialization were found to increase EFP. [Roy \(2023\)](#) investigated the effects of FDI, RE and NRE on the EFP in India from 1990 to 2016. Using the ARDL and the study found that FDI, RE, and GDP reduce EFP in the long term, while non-renewable energy consumption and trade openness increase it. [Azimi and Rahman \(2024\)](#) explored the nexus between RE and ecological footprint in 74 developing countries from 2000 to 2022 using a dynamic panel threshold regression method. The results revealed a non-linear relationship between RE and EFP, with significant thresholds for fiscal capacity (1.870), human development index (0.736), and institutional quality index (0.311), above which renewable energy effectively reduces EFP. Below these thresholds, the impact becomes insignificant.



2.6 Theoretical review and conceptual framework

There are three theories of environmental quality (EQ): such as urban environmental transition theory (UET), compact city theory (CCT), and ecological modernization theory (EMT) (Azam et al., 2022b). The UET clarifies the fact that significant industrialization leading to high emissions is a common feature of metropolitan centers. However, the idea also suggested that because urban residents are often wealthier than those who live in rural regions, they are more likely to be concerned about promoting environmental quality and may take many steps to reduce pollution. The CCT claims that public infrastructure, including the water supply, healthcare, education, and transportation systems, is harmed by urbanization. According to CCT, when the economy grows, there is a greater chance of environmental harm occurring. Strategies for planned urbanization may be helpful in reducing these negative consequences. The idea also proposed that governments should shift from being increasingly dependent on the industrial sector to service-based economies in order to reduce the increased risks of environmental damage (Azam et al., 2022b). Figure 1 shows the conceptual framework that explains how combining institutional quality and renewable energy reduces the ecological footprint. The combination of IQ and renewable energy significantly lessens the EFP through a multi-channel approach. Strong policies,

effective governance, investment in research and development, and public awareness form the backbone of IQ, facilitating the adoption of RE. Policy and regulation channels provide financial incentives, legal frameworks, and international collaboration to support clean energy initiatives. Innovation and research focus on developing advanced technologies and modernizing grid infrastructure to enhance energy efficiency. Education and advocacy promote public awareness, community involvement, and the implementation of energy-efficient building standards. These actions lead to increased renewable energy usage, lower carbon emissions, and ultimately, the reduction of the ecological footprint and climate change mitigation.

2.7 Literature summary and literature gap

The nexus between GLO and EFP. Van Tran et al. (2024) and Eweade et al. (2024) found that GLO positively affects the EFP, while Sabir and Gorus (2019) reported that globalization worsens environmental conditions. Ibrahiem and Hanafy (2020) and Farooq et al. (2022) found that GLO helps reduce environmental degradation, but its effects vary by country and type of GLO. Sun et al. (2023) and Pata et al. (2024) highlighted the complex, nonlinear relationship between GLO, energy consumption, and EFP, with GLO reducing specific environmental impacts.

TABLE 1 Literature summary.

Authors	Country/Time period	Method	Findings
Globalization and environment			
Van Tran et al. (2024)	Indonesia, 1971 to 2019	ARDL and NARDL	The positive shock of GLO has a positive and statistically significant impact on the EFP
Eweade et al. (2024)	United Kingdom, 1970 to 2015	ARDL	GLO contribute positively to the EFP
Sabir and Gorus (2019)	South Asian countries, 1975–2017	ARDL	The measures of GLO such as FDI, trade openness, and KOF index have positive and statistically significant effect on EFP
Ibrahiem and Hanafy (2020)	Egypt, 1971 to 2014	FMOLS and DOLS	Empirical results of FMOLS and DOLS methods show that real income and fossil fuel consumption are responsible for deteriorating the environment, while GLO and population are found to mitigate it
Ansari et al. (2021)	Top RE consuming countries, 1991–2016	ARDL	Negative impact is observed in case of RE consumption, GLO and urbanization on EFP
Yilanci and Gorus (2020)	14 MENA (Middle East and North Africa) countries, 1981–2016	Panel Fourier Toda-Yamamoto approach	Empirical results highlight that EFP Granger causes economic, trade, and financial GLO for the panel. Besides, it is found that financial GLO has a predictive power to predict further values of environmental degradation in the MENA countries
Farooq et al. (2022)	180 countries, 1980–2016	Panel quantile regression	Empirical results show that GLO helps to ameliorate environmental degradation. Panel quantile regression results also support the favorable role of GLO mainly for economies with existing low levels of carbon emissions
Sun et al. (2023)	BRICS countries	Quantile-on-quantile approach	A positive effect of GLO on the EFP is found at the most quantiles of the EFP in China, South Africa. For Brazil, India, and Russia, the negative impact occurs at most quantiles of the EFP.
Villanthenkodath and Pal (2023)	India, 1990–2018	ARDL	Economic GLO reduces the EFP in the long-run
Pata et al. (2024)	BRICS countries, 1992–2020	Panel common correlated effects estimator	GLO is reduces five of the seven EFP indicators
Industrialization and Environment			
Li and Lin (2015)	panel dataset of 73 countries, 1971–2010	Threshold regression models	(1) In the middle-/low-income and high-income groups, IND decreases energy consumption but increases CO2 emissions. (2) For the middle-/high-income group IND was found to have an insignificant impact on energy consumption and CO2 emissions. (3) From the population perspective, it produces positive effects on energy consumption, and also increases emissions except for the high-income group
Mentel et al. (2022)	44 Sub-Saharan African countries, 2000–2015	Two-step system GMM estimator	The share of industry in GDP has a significant positive impact on CO2 emissions
Azam et al. (2022a)	Six-member countries from the OPEC, 1975–2018	Fixed-effect	Empirical estimates shows that regressors, namely urbanization, IND, international trade, and energy use increase environmental pollution
Quito et al. (2023)	106 economies worldwide, 1995–2017	Quantile regression techniques	IND affects the lower quantiles negatively and significantly but affects the upper quantiles positively
Ullah and Lin (2024)	Pakistan, 1985 to 2022	dynamic ARDL	IND and urbanization upsurge the EFP while export diversification decreases
Financial Development and Environment			
Ashraf et al. (2022)	global sample of 124 economies	Two-step system GMM	Financial institutions' development has an inverted-U relationship with EFPs, while financial markets' development has an inverse-U relationship due to declining scale effects and rising technological effects

(Continued on following page)

TABLE 1 (Continued) Literature summary.

Authors	Country/Time period	Method	Findings
Tamazian et al. (2009)	BRIC countries, 1992–2004	Standard reduced-form modeling approach and controlling for country-specific unobserved heterogeneity	Higher degree of economic and financial development decreases the environmental degradation
Tamazian and Rao (2010)	24 transition economies, 1993–2004	standard reduced-form modelling approach to control for country-specific unobserved heterogeneity and GMM estimation to control for endogeneity	The results support the EKC hypothesis while confirming the importance of both IQ and financial development for environmental performance
Khalid et al. (2021)	SAARC countries, 1990 to 2017	AMG	Financial development weakly impacts SAARC countries, enhancing pollution in Bangladesh and Sri Lanka, but improving environmental quality in Nepal, and trade openness only in Nepal
Baloch et al. (2019)	panel of 59 BRI countries, 1990 to 2016	Driscoll-Kraay panel regression model	Findings shows that financial development increases EFP
Aslam et al. (2023)	43 middle income and 45 high income countries, 1990 to 2020	Panel Quantile Regression	Result shows that sophisticated financial development has mixed effects on EFPs in middle income countries, with China and higher income countries showing the most significant decline
Saqib et al. (2024)	top-ten countries with the biggest EFP, 1990 to 2019	panel causality approach	Financial development and the use of non-RE have been shown to be detrimental to the environment
Institutional quality and Environment			
Azimi and Rahman (2023)	G20 countries, 2000 to 2022	Generalized Autoregressive Conditional Heteroskedasticity	IQ is highly influential in eliminating the adverse impact of external shocks on EFP
Obobisa et al. (2022)	25 African countries, 2000 to 2018	AMG and common correlated effects mean group (CCEMG) estimators	IQ has a positive impact on CO2 emissions
Khan H. et al. (2022)	global panel, 2002 to 2019	two-step system GMM	Result indicates that while many countries' quality institutions struggle to mitigate environmental factors, the interaction term confirms the significant moderating effect of all explanatory variables on environmental quality
Sheraz et al. (2022)	64 BRI countries, 2003–2019	second-generation methodological approach	GLO and IQ both enhance negative environmental externalities from financial development, while suppressing positive externalities from RE and human capital
Dam et al. (2024)	OECD countries	three different models	The impact of IQ on deterioration is positive and significant in the long run
Addai et al. (2024)	N-11 countries, 1990 to 2022	CS-ARDL	Result shows that economic growth often leads to environmental degradation, but increasing RE consumption can reduce it if IQ positively impacts pro-environmental outcomes
Renewable energy and Environment			
Li et al. (2022)	120 countries, 1995 to 2014	threshold panel regression model	RE has a positive impact on EFP
Sahoo and Sethi (2021)	Developing countries, 1990 to 2016	FMOLS and DOLS approach	RE reduces the EFP or improves environmental quality
Nathaniel et al. (2020)	MENA countries, 1990 to 2016	AMG	RE does not contribute meaningfully to environmental quality, while non-RE consumption significantly adds to environmental degradation
Lu (2020)	13 Asian countries, 1973–2014	ARDL	Energy consumption have a positive impact on the EFP
Sharma et al. (2020)	eight developing countries of Asia, 1990 to 2015	ARDL	Result shows that long-term cointegration of variables like <i>per capita</i> income, nonRE usage, urbanization, fertility rate, and population density significantly drives environmental pollution, and RE consumption restores it

(Continued on following page)

TABLE 1 (Continued) Literature summary.

Authors	Country/Time period	Method	Findings
Dogan et al. (2020)	BRICS countries, 1980 – 2014	FMOLS DOLS, and AMG	Result shows that population, energy intensity and energy structure are vital determinants of environmental degradation
Lei et al. (2022)	China, 1991 to 2019	non-linear ARDL	Negative shocks in energy efficiency and RE consumption negatively impact long-term CO2 emissions, while positive shocks have short-term positive effects
Appiah et al. (2023)	29 OECD countries, 1990 to 2020	CS-ARDL	RE has a positive impact on reducing EFPs, whereas innovation improves the environmental quality
Roy (2023)	India, 1990 to 2016	ARDL model	RE has a negative and substantial impact on EFP in the long term
Azimi and Rahman (2024)	74 developing countries, 2000 to 2022	Dynamic panel threshold regression	RE consumption significantly reduces EFPs when fiscal capacity, human development, and IQ are exceeded, but becomes statistically insignificant when these indicators are below

Villanthenkodath and Pal (2023) found that economic GLO lowers EFP in India while economic growth increases it, emphasizing the need for balanced policies. The nexus between IND and EFP. Xu and Lin (2015) and Li and Lin (2015) found that IND drives environmental deterioration by increasing energy demand and CO2 emissions. Liu and Bae (2018) showed that rapid IND in China led to severe environmental damage. Quito et al. (2023) and Azam et al. (2022b) reported that IND worsens environmental degradation, with effects varying across income levels and regions, while renewable energy and urbanization can mitigate damage. Ullah and Lin (2024) confirmed that IND increases the EFP in Pakistan, suggesting sustainable policies and eco-friendly technologies to reduce environmental harm. The nexus between FD and EFP. Ashraf et al. (2022) and Aslam et al. (2023) found an inverted U-shaped relationship between FD and the EFP, where advanced FD helps reduce environmental degradation. Tamazian et al. (2009) and Tamazian and Rao (2010) highlighted the role of economic liberalization and financial openness in lowering CO2 emissions, while Khalid et al. (2021) reported mixed effects of FD on environmental quality in SAARC countries. Baloch et al. (2019) found that FD increases EFP in BRI nations. In contrast, Saqib et al. (2024) showed that FD and non-renewable energy worsen environmental conditions, but environmental innovations and green growth can mitigate the impact.

The nexus between IQ and EFP. Azimi and Rahman (2023) and Addai et al. (2024) found that IQ reduces the EFP and enhances the positive impact of renewable energy on environmental sustainability. Obobisa et al. (2022) and Khan H. et al. (2022) reported mixed findings, with IQ reducing CO2 emissions in some cases but failing to mitigate environmental degradation in others, particularly in Africa. Sheraz et al. (2022) showed that IQ offsets the adverse environmental effects of FD but amplifies GLO's impact in BRI economies. Dam et al. (2024) highlighted that while green growth improves environmental outcomes, IQ may not always reduce long-term environmental degradation, suggesting a need for stronger institutional frameworks and policies. The nexus between RE and EFP. Li et al. (2022) and Azimi and Rahman (2024) found that RE reduces the EFP, but its effectiveness depends

on factors like fiscal capacity, human development, and IQ. Nathaniel et al. (2020) and Sharma et al. (2021) reported that non-renewable energy (NRE) worsens environmental degradation, while RE has limited or varying impacts. Appiah et al. (2023) and Roy (2023) highlighted that RE, along with environmental policies and innovation, improves environmental quality, though IND and trade openness may offset these gains. Lei et al. (2022) showed that positive RE and energy efficiency shocks reduce CO2 emissions, emphasizing the importance of consistent RE adoption for sustainability (Table 1).

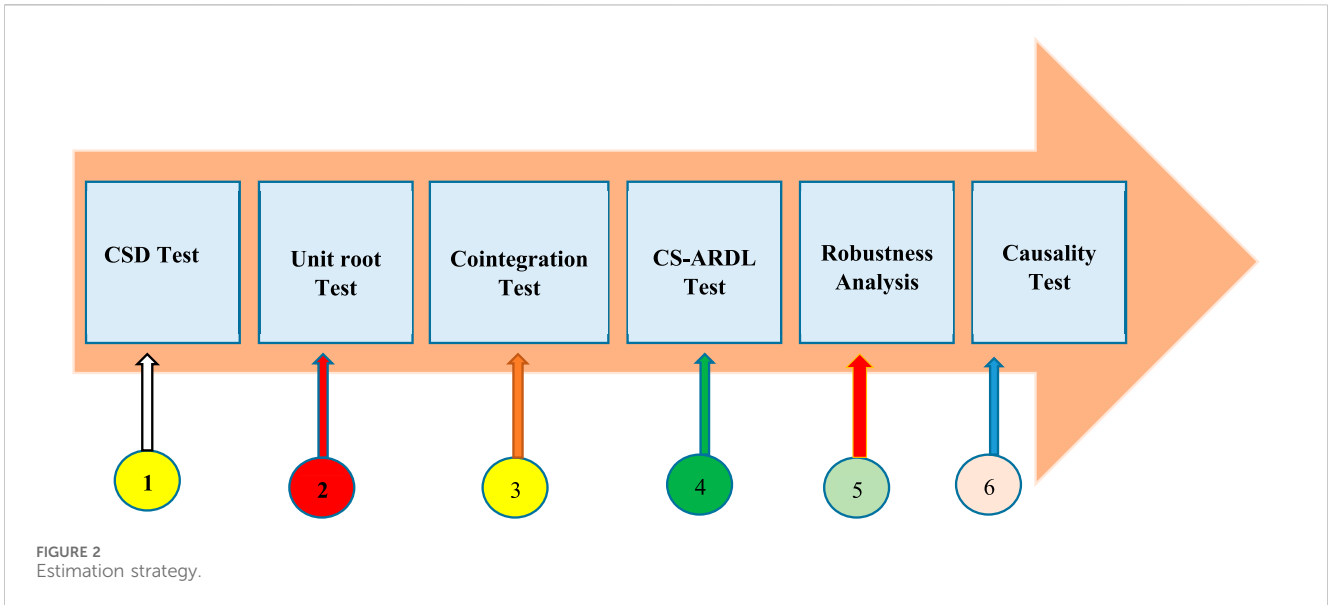
Therefore, the following gaps in the empirical literature may be found after reviewing the pertinent studies in the available literature: (1) it is evident that not many publications have used the ecological footprint for measuring environmental quality in significant samples of SAARC countries (2) There is little research on panel studies of the connection between environmental impact, industrialization, FD, institutional quality and renewable energy in SAARC countries (3) this study make an index for institutional quality from governance indicators for SAARC countries (4) The ecological footprint of industrialization, FD, and institutional quality has generally been the subject of individual (isolated) research in the past, with little attention paid to the combined (interaction) effects of these factors. In response to this context, this study utilizes panel data from 1996 to 2022 to mitigate the research gaps in the forgoing studies.

3 Materials and methods

3.1 Model specification

To examine the impact of GLO, IND on EFP for six SAARC countries and the role of IQ and RE. The empirical model of this study derived from prior studies:

$$EFP_{it} = \beta_0 + \beta_1 IQ_{it} + \beta_2 FD_{it} + \beta_3 GLO_{it} + \beta_4 IND_{it} + \beta_5 GDP_{it} + \beta_6 RE_{it} + e_{i,t} \quad (1)$$



where Equation 1, EFP, IQ, FD, GLO, IND, GDP, and RE, represents ecological footprint, institutional quality index, financial devolvement, globalization, industrialization, Gross domestic product and renewable energy respectively. Where the subscript i, t and e_{it} , represent the countries, time periods and residual term. EFP, is a dependent variable while IQI, FD, GLO, IND, NEC, REC, FDI, and TRD are independent variables. β_0 is intercept, while β_1 to β_6 are the coefficient slope. We convert all of the data to natural logarithm in order to prevent data sharpness and Heteroscedasticity (Azam et al., 2023) expect IQI, because it includes negative value.

3.2 Estimation Strategy

Figure 2 depicts the estimating approach used in this study:

3.2.1 Cross-sectional dependence tests

Cross-sectional dependency (CSD) refers to the phenomenon where observations, e.g., countries, regions, or entities in a dataset, correlate. This dependency arises due to shared shocks, spatial proximity, or economic interdependencies. Ignoring the CSD can lead to biased and inefficient estimates in panel data analysis. We used CD tests and the Lagrange multiplier (LM) to examine the CSD test. The formulae are given in Equations 2, 3, respectively.

$$LM = J \sum_{i=1}^{K-1} \sum_{j=i+1}^K \hat{\alpha}_{ij}^2 \tag{2}$$

$$CD = \sqrt{\frac{2K}{N(N-1)}} \left[\sum_{i=1}^{K-1} \sum_{j=i+1}^K \hat{\alpha}_{ij}^2 \right] \tag{3}$$

where K is sample size, T is time period and $\hat{\alpha}_{ij}^2$ represent the residuals correlation between nation i and nation j respectively (See, Uddin et al., 2023b).

3.2.2 Panel unit root tests

After the CSD, a panel unit root test is used to determine stationarity, essential for identifying its statistical properties. Stationarity ensures that the series' mean, variance and autocovariance remain constant over time, critical for reliable regression analysis and forecasting. The test also helps prevent spurious results in models involving non-stationary data. The traditional OLS estimators will produce erroneous estimates if the order of integration is ignored. Cross-sectional dependence (CD) causes the unit root of Levin et al. (2002) to provide estimates that are inaccurate. In this regard, the panel unit root tests created by CIPS by Pesaran (2007) are used in this work. See Equations 4, 5.

$$\Delta Z_{it} = \omega_i + \omega_i Z_{it-1} + \omega_i \bar{Y}_{t-1} + \sum_{i=0}^p \omega_{i1} \Delta \bar{Z}_{t-1} + \sum_{i=1}^p \omega_{i2} \Delta Z_{it-1} + e_{it} \tag{4}$$

$$\widehat{CIPS} = \frac{1}{K} \sum_{i=1}^n CADF_i \tag{5}$$

In Equation 6, \bar{Y}_{t-1} and $\Delta \bar{Z}_{t-1}$ link to the cross-sectional average.

3.2.3 Cross sectional autoregressive distributed lag (CS-ARDL) model

The Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model is applied when variables in a panel dataset exhibit mixed orders of integration, i.e., some are stationary at the level I (0), and others at the first difference I (1). This flexibility allows CS-ARDL to estimate both short- and long-run relationships without requiring all variables to be integrated in the same order. Examine the Equation 6 given the conventional panel ARDL. Where in this case $Z_{i,t}$ denotes ecological footprint (EFP) and represent Response variable. The $Z_{i,t-j}$ signifies lagged of the Response variable, $Y_{i,t-j}$ is the course of independent variables, i.e., IQI, FD, GLO, IND, NEC, REC, FDI, and TRD respectively. The term $Z_i, \phi_{ij}, \Psi_{ij}, e_{it}$ and subscripts i and t represent the fixed effects, coefficient of the lagged regressand, $k \times 1$ coefficient vectors (lagged regressors), error term and countries and time period.

$$Z_{it} = \sum_{j=1}^p \phi_{ij} Z_{i,t-j} + \sum_{j=0}^q \Psi_{ij} Y_{i,t-j} + X_i + e_{it} \tag{6}$$

Results are biased when CD is present in the standard Panel ARDL described in Equation 6 (Phillips and Sul, 2003). Consequently, the issue of the presence of CD is addressed by employing an alternative estimating method called the CS-ARDL method. The CS-ARDL is superior to other panel ARDL models because it effectively addresses CSD by incorporating cross-section averages of variables. Unlike standard panel ARDL models, it provides robust and efficient long-run estimates even when residuals are correlated across units. Moreover, CS-ARDL mitigates bias from unobserved common factors, ensuring more reliable inference in heterogeneous panel settings. The CS-ARDL assumes CSD among panel units, which is addressed using cross-section averages of variables. Long-run slope homogeneity is required to ensure consistent estimation across units. Additionally, the model assumes stationarity or weak dependence in error terms to derive valid inferences. The CS-ARDL's limitation is that it requires a large time dimension (T) for reliable estimation, making it less effective in short panels. It may also overcorrect for cross-sectional dependence, reducing efficiency when dependence weakens. In addition, the model is computationally complex and sensitive to the correct specification of common factors. Chudik and Pesaran (2013) stated that additional lags for the cross-sectional averages of the regressors should be included to the ARDL specification in Equation 6.

The revised formula, which now includes the cross-sectional lag factor, is as follows:

$$EFP_{it} = \sum_{j=1}^p \phi_{ij} EFP_{i,t-j} + \sum_{j=0}^q \Psi_{ij} Y_{i,t-j} + \sum_{j=0}^r \hat{\beta}_{ij} \bar{W}_{t-1} + X_i + e_{it} \tag{7}$$

where in Equation 7, $\bar{W}_{t-1} = (\overline{EFP}_{i,t-j}, \bar{Y}_{i,t-j})$ are the averages of regressand and regressor, while \bar{W} showed cross-section averages and avoids the CD. Moreover, the superscript $p, q,$ and r represent each variable lags, number of lags and number of lags of the cross-sectional averages to be involved respectively (Azam et al., 2022b; Uddin et al., 2023b). The long run coefficient estimates for the CS-ARDL technique may be calculated as follows:

$$\hat{\xi}_{CS-ARDL,ij} = \frac{\sum_{j=0}^q \hat{\Psi}_{ij}}{1 - \sum_{j=1}^p \hat{\phi}_{ij}}$$

Equation 8 can also be expressed in error-correcting form as shown below:

$$\begin{aligned} \Delta EFP_{it} = & \vartheta_i \left[EFP_{i,t-j} - \lambda_{i,j} Y_{i,t} \right] - \sum_{j=1}^{p-1} \phi_{ij} \Delta_l EFP_{i,t-1} + \sum_{j=0}^q \Psi_{ij} \Delta Y_{i,t} \\ & + \sum_{j=0}^r \hat{\beta}_{ij} \bar{W}_{t-1} + X_i + e_{it} \end{aligned} \tag{8}$$

where $\Delta_l = t - (t - 1)$

3.2.4 Panel granger causality

The CS-ARDL model does not gives the causality estimates amongst the variables. Therefore, in this study, the) panel causality

test Dumitrescu and Hurlin (2012) is also applied. The following Equations 9–20, shows the basic specification of DH test.

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta IQ_{it-k} + e_{1it} \tag{9}$$

$$\Delta IQ_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta IQ_{it-k} + e_{2it} \tag{10}$$

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta FD_{it-k} + e_{1it} \tag{11}$$

$$\Delta FD_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta FD_{it-k} + e_{2it} \tag{12}$$

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta GLO_{it-k} + e_{1it} \tag{13}$$

$$\Delta GLO_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta GLO_{it-k} + e_{2it} \tag{14}$$

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta IND_{it-k} + e_{1it} \tag{15}$$

$$\Delta IND_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta IND_{it-k} + e_{2it} \tag{16}$$

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta GDP_{it-k} + e_{1it} \tag{17}$$

$$\Delta GDP_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta GDP_{it-k} + e_{2it} \tag{18}$$

$$\Delta EFP_{it} = \alpha_{1j} + \sum_k \alpha_{11ik} \Delta EFP_{it-k} + \sum_k \alpha_{12ik} \Delta RE_{it-k} + e_{1it} \tag{19}$$

$$\Delta RE_{it} = \alpha_{2j} + \sum_k \alpha_{21ik} \Delta EFP_{it-k} + \sum_k \alpha_{22ik} \Delta RE_{it-k} + e_{2it} \tag{20}$$

So, therefore, $H_0: \alpha_{1j} = 0$ or $H_0: \alpha_{2j} = 0$. If the H_0 is rejected IQ, FD, GLO, IND, GDP and RE cause EFP.

For the robustness analysis, we used the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators to estimate long-run relationships. FMOLS corrects for endogeneity and serial correlation in the residuals by using non-parametric adjustments, providing robust and efficient estimators for long-run parameters (Phillips and Hansen, 1990). DOLS extends the ordinary least squares by including leads, lags, and contemporaneous differences of the explanatory variables to address endogeneity and autocorrelation, ensuring unbiased estimators (Stock and Watson, 1993).

3.3 Variables description and data source

Data for the panel of six SAARC economies (Sri Lanka, Pakistan, Nepal, India, Bhutan, and Bangladesh) from 1996 to 2022 are used for analysis. Table 2 lists the variables, along with their symbols, units of measurement, and data sources. The IQ index emerged from six governance indicators, such as Control of Corruption (CC), Government Effectiveness (GE), Political Stability and Absence of Violence/Terrorism (PSAV), Regulatory Quality (RQ), Rule of Law (RL) and Voice and Accountability (VA) by using the principal component analysis (PCA). The same index was used by Obobisa et al. (2022), Sheraz et al. (2022), Uddin et al. (2023a), Uddin et al. (2024), and Cui et al. (2024). The results of the PCA are provided in Table 3. The first principal component (Comp1) accounts for 61.2% of the variation in the dataset, making it the most suitable component for developing the IQ index for this study.

TABLE 2 Data sources and variables description.

Variables	Symbol (expected sign)	Unit	Data sources	Variable used by
Ecological footprint	EFP	Metric tons <i>per capita</i>	https://Data.footprintnetwork.org/	Usman et al. (2021), Sahoo and Sethi (2021), Uddin et al. (2023c)
Institutional quality index	IQ (-)	Index emerged from governance indicators	World Bank	Obobisa et al. (2022), Sheraz et al. (2022)
Financial devolvement	FD (-)	Index	World Bank	Tamazian et al. (2009), Khalid et al. (2021), Nathaniel et al. (2020)
Globalization	GLO (+)	index	World Bank	Chen et al. (2019), Zaidi et al. (2019)
Industrialization	IND (+)	Constant 2015 US\$	World Bank	Azam et al. (2022b), Mentel et al. (2022)
Gross domestic product	GDP (+)	Constant 2015 US\$	World Bank	Du et al. (2023)
renewable energy	RE (-)	%	World Bank	Sahoo and Sethi (2021), Lei et al. (2022)

TABLE 3 PCA output of Institutional quality index.

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	3.672	2.482	0.612	0.612
Comp2	1.190	0.481	0.198	0.810
Comp3	0.709	0.495	0.118	0.928
Comp4	0.214	0.073	0.036	0.964
Comp5	0.141	0.068	0.024	0.988
Comp6	0.073	—	0.012	1.000

Principal components (eigenvectors)						
Variable	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
CC	0.471	-0.295	-0.078	-0.066	-0.635	0.527
GE	0.479	-0.102	-0.142	-0.614	0.589	0.128
PSAV	0.416	-0.421	0.222	0.683	0.364	-0.050
RQ	0.262	0.631	-0.581	0.378	0.105	0.206
RL	0.500	0.128	-0.037	-0.098	-0.325	-0.786
VA	0.239	0.558	0.765	-0.036	0.003	0.210

4 Results and discussion

4.1 Basic statistics

Table 4, shows the descriptive statistics, the mean value of EFP, IQ, FD, GLO, IND, GDP, and RE are 0.841, -0.460, 0.244, 46.248, 23.376, 7.162 and 4.053 respectively. Whereas the standard deviation of EFP, IQ, FD, GLO, IND, GDP, and RE are 0.815, 0.456, 0.108, 10.431, 2.180, 0.554 and 0.354 respectively. The Jarque-bera statistics reveal that only IND is normally distributed.

4.2 Cross-sectional dependency and panel unit root tests estimates

Table 5 presents the estimates of the CSD test, indicating that all statistics reject the null hypothesis of no CSD at the 1% significance level. Table 6 displays the estimates of the LLC and CIPS tests at both level and first difference. The results from the LLC test suggest that only GLO is stationary at level. Meanwhile, the CIPS test indicates that EFP and GLO are stationary at level, while all other variables become stationary at first difference.

TABLE 4 Descriptive statistics.

	EFP_{it}	IQ_{it}	FD_{it}	GLO_{it}	IND_{it}	GDP_{it}	RE_{it}
Mean	0.841	-0.001	0.244	46.248	23.376	7.162	4.053
Median	0.477	0.353	0.215	47.020	23.783	7.121	3.993
Maximum	3.115	4.290	0.539	62.652	27.261	8.411	4.538
Minimum	0.210	-3.047	0.069	22.655	18.984	6.197	3.250
Std. Dev	0.815	1.922	0.108	10.431	2.180	0.554	0.354
Skewness	1.759	0.362	0.962	-0.418	-0.179	0.380	-0.126
Kurtosis	4.464	1.989	2.945	2.344	2.237	2.413	1.963
Jarque-Bera	91.365***	9.352***	23.286***	7.096**	4.473	5.803*	7.163**
Probability	0.000	0.009	0.000	0.029	0.107	0.055	0.028

Note: ***, **, and * shows 1%, 5% and 10% significance level.

TABLE 5 Cross-sectional dependence tests results.

Pesaran CD	3.349***	0.000
Breusch-Pagan LM	105.933***	0.000
Pesaran scaled LM	16.602***	0.000
Bias-corrected scaled LM	16.41469***	0.000

Note: Asterisks *** denotes significance at 1% level of significance. EFP = f (IQ, FD, GLO, IND, GDP, RE).

4.3 CS-ARDL estimates

Table 7 shows the panel CS-ARDL findings. In the long run, IQ, FD, and RE have a negative effect on ecological footprint, while GLO, IND, and GDP positively affect EFP. The coefficient of IQ is -0.02192, a 1-unit increase in institutional quality that leads to a 0.02% reduction in the ecological footprint, highlighting the role of governance in environmental sustainability. IQ reduces environmental degradation by enforcing strong regulations and ensuring industries comply with pollution controls and sustainability standards. It curbs corruption and enhances transparency, preventing the misuse of environmental funds and ensuring efficient policy implementation. Additionally, effective

governance promotes green innovation and RE adoption, driving sustainable economic growth while reducing ecological harm. Sheraz et al. (2022) stated that institutional quality decreases the negative environmental externality in BRI countries. Effective institutions play an important role in avoiding environmental costs. Government stability is critical for the quality of institutional performance and, as a result, for productive environmental management. Obobisa et al. (2022) reported that IQ negatively impacts CO₂e in African countries. On the contrary, Khan A. A. et al. (2022) stated that many nations' institutions' quality can now not sufficiently reduce each environmental factor's harmful effects and preserve the environment.

The coefficient of FD is negative, indicating that a 1% rise in FD leads to reduced EFP by 0.70007%. Tamazian and Rao (2010) showed that economic liberalization results in environmental degradation and a lack of excellent institutional efficiency. Khalid et al. (2021) found that in the case of Bangladesh and Sri Lanka, financial growth greatly raises the degree of pollution. However, it enhances Nepal's environmental quality. Contrarily, financial growth favors the ecological footprint in BRI nations (Baloch et al., 2019). On contrary, Baloch et al. (2019) indicated that financial growth has a favorable effect on EFP, which suggests that financial development causes a rise in EFP in BRI nations. EFP and economic growth are positively correlated in BRI countries. In contrast, financial development contributes to environmental deterioration by

TABLE 6 Unit root test.

	LLC		CIPS	
	Level	1st difference	Level	1st difference
EFP_{it}	-0.285	-2.787***	-2.350**	-2.885***
IQ_{it}	0.806	-2.471***	-1.587	-2.246*
FD_{it}	1.344	-6.145***	-1.381	-3.360***
GLO_{it}	-3.476***	-4.451***	-2.212*	-3.875***
IND_{it}	1.597	-4.582***	-0.790	-4.432***
GDP_{it}	1.576	-3.592***	-1.236	-2.875***
RE_{it}	-0.431	-2.561***	-1.358	-3.365***

Note: ***, **, and * shows 1%, 5% and 10% significance level. The CIPS, critical value for 1%, 5% and 10% are -2.58, -2.33, and -2.21 respectively.

TABLE 7 CS-ARDL parameter estimates.

Variable	Coefficient	Std. Err	Z- stats	p-value	Lower interval	Upper interval
Long run coefficient						
IQ_{it}	-0.02192*	0.01021	-2.14673	0.08460	-0.04132	-0.00252
FD_{it}	-0.70007***	0.16042	-4.36405	0.00000	-1.10112	-0.29902
GLO_{it}	0.82907***	0.26668	3.10885	0.00350	0.30638	1.35176
IND_{it}	0.02683*	0.01362	2.00001	0.09250	0.00095	0.05271
GDP_{it}	0.27502	0.19812	1.38818	0.17280	0.03728	0.51276
RE_{it}	-0.30193**	0.10055	-3.00291	0.00460	-0.53320	-0.07067
Short run coefficient						
IQ_{it}	-0.12125***	0.02379	-5.09582	0.00000	-0.18074	-0.06177
FD_{it}	0.01268	0.02114	0.59996	0.55191	-0.00423	0.02959
GLO_{it}	0.04619	0.02920	1.58215	0.12154	-0.00052	0.09291
IND_{it}	0.10615***	0.03511	3.02337	0.00012	0.02891	0.18339
GDP_{it}	-0.00285	0.01029	-0.27718	0.78398	-0.00903	0.00333
RE_{it}	-0.03795**	0.01413	-2.68623	0.01050	-0.06409	-0.01181
$ECM (-1)$	-0.04197***	0.00555	-7.56352	0.00000		

Note: ***, **, and * shows 1%, 5% and 10% significance level. Dependent variable: Ecological footprint.

encouraging and enabling financing for purchasing mechanical machinery, electrical gadgets, vehicles, and residences. These facilities let company owners expand their operations and set up new equipment and plants, which worsen environmental quality by increasing the concentration of CO₂e in the atmosphere (Majeed and Mazhar, 2019).

The coefficient shows that Globalization positively affects EFP, indicating that a 1% rise in Globalization leads to rise the EFP by 0.82907%. Globalization revolutionized the world over the past decade, and nations are now linked socially, economically, and politically. These aspects impact the environment (Dreher et al., 2008). On the contrary, Figge et al. (2017) reported that economic GLO leads to greater consumption and imports with a negative environmental impact. According to Kirikkaleli et al. (2021) reported that GLO donates to environmental deterioration by raising Turkey's EFP. Similar conclusions were reached for the developing countries of South Asia by Sabir and Gorus (2019), who found that these economies' decisions to embrace Globalization have worsened their environmental conditions because their EFP numbers have increased along with increased globalization activities. In contrast, Farooq et al. (2022) highlight that GLO aids in reducing environmental deterioration.

The coefficient of industrialization is positive, which indicates that a 1% rise in the IND led to a rise in EFP of 0.02683%. As a consequence of the industrial revolution, industrialization has emerged as the primary path towards economic and social modernization. Nevertheless, both strategies promote the rapid growth of fossil fuel use and lead to significant CO₂e and other GHG emissions. Sharp surges in the demand for fossil fuels and CO₂e also convey these routes. According to Li and Lin (2015), industrialization was linked to higher energy demand and modified energy consumption patterns at the early economic growth stages, leading to higher CO₂e. Mentel et al. (2022) discovered that the IND positively impacts CO₂e. The coefficient of GDP has a positive effect on EFP but statistically insignificant; more

specifically, a 1% surge in the GDP led to a rise in EFP of 0.27502%. However, the statistical insignificance of this coefficient indicates that the relationship is not strong enough to be considered meaningful or reliable. An insignificant GDP coefficient for EFP may indicate non-linear effects, where GDP impacts the footprint differently at various income levels (e.g., the Environmental Kuznets Curve). It could also result from omitted variable bias, missing factors, and threshold effects. The finding is consistent with the line of (Du et al., 2023).

The coefficient of renewable energy is negative, indicating that a 1% surge in RE reduces CO₂e by 0.431%. Renewable energy reduces the ecological footprint by decreasing reliance on fossil fuels, lowering carbon emissions and environmental degradation. It promotes sustainable resource use, reducing deforestation, air pollution, and water consumption. By replacing conventional energy sources, renewables help preserve ecosystems and mitigate climate change. The usage of renewables lowers habitat devastation caused by mining and drilling. Furthermore, RE technologies often demand less land and water than traditional energy sources. The finding is consistent with the finding of Appiah et al. (2023) that renewable energy contributes to reducing the ecological footprint in 29 OECD countries. Roy (2023) examined the impact of RE on EFP in India from 1990 to 2016. The results showed that renewable energy consumption and FDI and GDP reduce EF in the long run. Azimi and Rahman (2024) Identified a non-linear relationship between RE and EFP in 74 developing countries. Renewable energy reduces EF only when fiscal capacity, human development, and institutional quality exceed specific thresholds. Below these thresholds, its impact on EFP becomes insignificant. Du et al. (2023) found that energy productivity reduced the environmental damage in OECD economies. Meanwhile, Khan F. et al. (2024) found that RE enhances Pakistan's environmental sustainability.

In short run, CS ARDL estimates confirm that IQ, GDP, and RE have a negative effect on EFP, while FD, GLO, and IND have a negative

TABLE 8 Robustness checks.

Variables	FMOLS			DOLS		
	Coefficient	<i>t-ratios</i>	Prob	Coefficient	<i>t-ratios</i>	Prob
IQ_{it}	-0.04949***	-3.90129	0.00020	-0.03840***	-3.96024	0.00030
FD_{it}	-0.42299*	-1.85888	0.06640	-0.19848	-0.70940	0.48220
GLO_{it}	0.39931***	5.14710	0.00000	0.46762***	5.35888	0.00000
IND_{it}	0.03283*	1.81880	0.07230	0.04229**	2.46237	0.01820
GDP_{it}	0.08906	1.60131	0.11290	0.10864	1.76383*	0.08540
RE_{it}	-0.05631	-0.99803	0.32100	-0.05280	-0.93640	0.35470
R ²	0.544335			0.893871		
Adj. R ²	0.508089			0.747944		

Note: ***, **, and * shows 1%, 5% and 10% significance level. Dependent variable: Ecological footprint.

effect on EFP. The ECM (-1) coefficient is -0.04197, representing the speed of adjustment toward long-run equilibrium after a short-run shock. It means that about 4.2% of any disequilibrium from the previous period is corrected in the current period. The negative sign confirms convergence to equilibrium over time.

4.4 Robustness checks

Table 8 shows the results of Robustness analysis, this study employs both FMOLS and DOLS estimators to ensure the robustness and validity of the CS-ARDL findings. The results indicate that FD, RE, and IQ have adversely impacted EFP, suggesting enhanced environmental sustainability. In contrast, IND, GLO, and GDP have contributed positively to EFP, indicating an encouraging influence.

4.5 Panel causality analysis

In Table 9 shows the D-H causality test, it displays that a one-way causal linkage was exposed from ecological footprint to IQ index, Thus, EFP to IQ Index: The ecological footprint influences institutional quality, suggesting that environmental degradation or poor ecological outcomes can spur the need for stronger institutions to address sustainability and environmental issues. While one one-way causal linkage was exposed from ecological footprint to FD, implies that environmental degradation may impact financial systems, possibly leading to reduced investment or changes in financial priorities due to environmental concerns. One way causality expose from globalization to IQ index, globalization to FD, FD to industrialization, globalization to GDP. While bio-directional causality exists between FD and institutional quality index, GDP and institutional quality, renewable energy usage and institutional quality index, FD and GDP. RE and IQI, There is a mutual influence between renewable energy usage and institutional quality. A well-developed institutional framework can encourage the adoption of RE through supportive policies, and increased RE usage can promote institutional reforms focused on sustainability and environmental protection.

5 Conclusion and policy recommendation

This study examined the impact of globalization and industrialization on ecological footprint, focusing mainly on institutional quality and renewable energy between 1996 and 2022 using the CS-ARDL, FMOLS, and DOLS estimators. The finding showed that IQ, FD, and RE negatively affect EFP, while GLO, IND, and GDP positively affect EFP. To prevent future degradation of the environment, these nations must first take appropriate action in relation to globalization and industrialization in their economy. From a policy perspective, this study contributes to the existing literature by proposing redesigned sustainable development strategies to address key issues in the South Asian region. Current policies often fail to encourage adopting and developing sustainable technologies that can reduce waste, minimize energy consumption, and improve efficiency in South Asian economies. Governments should prioritize policies that promote the development and implementation of RE sources, such as wind, solar, and hydropower, to reduce dependence on fossil fuels and lower CO_{2e}. Policies must be restructured to ensure that economic growth does not come at the expense of environmental degradation. Strategies should also include promoting sustainable forest management practices, such as reforestation, reducing deforestation rates, and encouraging sustainable methods to balance economic growth with conservation.

Moreover, Policies should promote sustainable consumption and production patterns to further reduce the EFP of South Asian economies. This includes reducing waste and pollution, encouraging the use of RE, and fostering practices that support environmental sustainability while maintaining economic progress. SAARC economies should adopt Germany's Renewable Energy Act. This policy incentivized renewable energy adoption through feed-in tariffs, significantly increasing green energy production. SAARC countries could implement similar tariff structures to accelerate solar and wind power investments. China's anti-pollution measures, strict emissions regulations, and carbon trading schemes have also helped reduce industrial pollution. Adapting such market-based mechanisms could help SAARC nations curb emissions while promoting cleaner industries. South Asian economies should reduce geopolitical risks and enhance regional stability by fostering economic

TABLE 9 Results of Panel causality test.

	EFP_{it}	IQI_{it}	FD_{it}	GLO_{it}	IND_{it}	GDP_{it}	RE_{it}
EFP_{it}	—	(9.542)*** [5.345]	(5.694)** [2.424]	(1.992) [-0.386]	(4.459) [1.487]	(3.342) [0.639]	(2.552) [0.040]
IQI_{it}	(1.679) [-0.623]	—	(15.519)*** [9.881]	(3.422) [0.699]	(4.013) [1.148]	(6.232)*** [2.832]	(5.344)** [2.158]
FD_{it}	(2.133) [-0.278]	(6.318)*** [2.898]	—	(2.896) [0.300]	(7.179)*** [3.551]	(5.291)** [2.119]	(2.752) [0.192]
GLO_{it}	(1.474) [-0.778]	(6.271)*** [2.862]	(5.710)** [2.436]	—	(3.253) [0.572]	(6.548)*** [3.072]	(1.128) [-1.041]
IND_{it}	(4.035) [1.165]	(2.534) [0.026]	(3.732) [0.935]	(2.905) [0.307]	—	(0.752) [-1.327]	(2.485) [-0.012]
GDP_{it}	(3.687) [0.901]	(8.771)*** [4.760]	(6.076)*** [2.714]	(2.729) [0.173]	(3.221) [0.547]	—	(2.232) [-0.203]
RE_{it}	(1.160) [-1.017]	(8.476)*** [4.535]	(4.176) [1.272]	(1.468) [-0.783]	(5.060)* [1.943]	(1.276) [-0.929]	—

***, ** and * represent a 1%, 5% and 10% level of significance. In (W-Stat.) and [Zbar-Stat.] respectively.

interdependence, diplomatic dialogue, and collaborative development initiatives among SAARC nations. Strengthen intra-SAARC trade and develop shared energy projects (e.g., cross-border RE grids) to create economic interdependence, reducing incentives for conflicts. Invest in joint infrastructure projects (e.g., roads, railways, and digital networks) to promote seamless economic integration and mutual economic benefits. Develop a cross-border renewable energy grid to facilitate electricity trade among SAARC nations, optimizing solar, wind, and hydro resources. Establish a regional financial mechanism to support renewable energy projects, sustainable infrastructure, and green technology innovation.

Furthermore, SAARC countries should strengthen institutional frameworks to align with global environmental policies like the Paris Agreement by enforcing stricter regulations on emissions and renewable energy adoption. Strengthening governance will enhance compliance and attract international climate financing. Policymakers should reform trade and investment regulations to ensure that globalization supports green technologies and sustainable practices. Strong institutions will help balance economic growth with environmental responsibility by promoting eco-friendly FDI. Strengthen the rule of law by ensuring strict enforcement of environmental regulations and penalizing violations such as illegal deforestation, pollution, and land encroachment. Establish fast-track environmental courts in SAARC nations to expedite cases against environmental offenders. Establish independent anti-corruption bodies within SAARC countries to investigate environmental crimes. Implement a regional digital tracking system for environmental funds to prevent misallocation. Governments should establish policy-academic partnerships to translate institutional quality and environmental sustainability research into actionable frameworks. Creating data-sharing platforms and think tanks will help policymakers implement evidence-based sustainability strategies. SAARC nations should establish a regional green fund to finance cross-border renewable energy projects and institutional reforms. Strengthening cooperation will enhance policy synchronization, ensuring a unified approach to climate resilience and sustainable development.

Lastly, this study acknowledges several limitations that can guide future research. One key limitation is the geographical scope, as the analysis focuses solely on selected economies of the SAARC member states, excluding developed, emerging, and other developing nations. Future research can extend the assessment to broader countries for a more comprehensive understanding. Additionally, this study incorporates only a limited set of variables while overlooking various

macroeconomic, demographic, social, and health-related factors that could significantly influence EFP. Future investigations can integrate these variables to capture a more holistic perspective. Moreover, this study relies on CS-ARDL, FMOLS, and DOLS estimators without considering asymmetric analysis or Quantile regression. Future research could employ these advanced econometric techniques to explore nonlinear relationships and distributional effects, thereby enriching the findings on EFP determinants.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

QL: Conceptualization, Writing—original draft, Writing—review and editing. SZ: Data curation, Formal Analysis, Methodology, Writing—original draft, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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