



# The dynamic nexus between biocapacity, renewable energy, green finance, and ecological footprint: evidence from South Asian economies

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## Abstract

Striking a balance between economic development and environmental sustainability has evolved into an important primary goal for international organizations, governments and the globe. In the modern era, world economies, particularly developing ones such as South Asian economies, aim to achieve economic growth while simultaneously improving the reduction of ecological footprint (EFP). Against this backdrop, this study explores the impact of economic growth, biocapacity, renewable energy use, natural resource rent, agricultural value-added, green finance and information and communication technology on the ecological footprint. The scope of the relationship among the variables is examined within the environmental Kuznets Curve (EKC) framework with a dataset from 1990 to 2017. The cross-sectional-augmented autoregressive distributed lag (CS-ARDL) approach was applied to estimate the variable's short and long-term interaction. The results indicated the existence of the EKC hypothesis in this region. In addition, agriculture value-added, natural resources, and biocapacity increase EFP. Further, renewable energy use, green finance, and ICT mitigate EFP. The Dumitrescu and Hurlin (D-H) causality test reflected a unidirectional causality association flowing from economic growth, renewable energy use, green finance, and agricultural value-added to EFP. Lastly, there exists a bidirectional nexus between natural resource rent, biocapacity, ICT, and EFP. The present research adds to the existing literature on the factors contributing to environmental pollution by presenting new insights from South Asian economies. This study also provides a reference point for policymakers and government entities in these regions to invest in cleaner technologies, ICT, and green finance to mitigate environmental pollution.

**Keywords** Economic growth · Natural resource · Agriculture · Information · Communication technology

## Abbreviations

COP 26	Conference of the parties 26	GDP	Gross domestic product
UNFCCC	United Nations Framework Convention on Climate Change conference	REU	Renewable energy use
SSE	South Asian economies	GFN	Green finance
EFP	Ecological footprint	NRR	Natural resource rent
BIO	Biocapacity	ICT	Information and communication technology
EGC	Economic growth	AGRIC-VA	Agriculture value-added
		EKC	Environmental Kuznets curve
		CS-ARDL	Cross-sectional-augmented autoregressive distributed lag
		CC-MG	Common correlated effect means group estimator
		AMG	Augmented mean group
		D-H	Dumitrescu–Hurlin
		SHT	Slope homogeneity test
		VIF	Variance inflation factor
		CSD	Cross-sectional dependency
		CADF	Cross-sectional augmented Dickey–Fuller
		CIPS	I'm Pesaran and Shin

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STIRPAT	Stochastic impacts by regression on population, affluence, and technology
WID	World development indicator
OECD	Organization for Economic Co-operation and Development

## Introduction

A recent climate change conference titled "COP26, the Glasgow Climate Pact" organized by the United Nations Framework Convention on Climate Change Conference (UNFCCC) in November 2021 in the UK highlighted the significance of reducing global climate change. Thus, all countries are encouraged to strengthen their mitigation strategies to help reduce environmental pollution globally. The Glasgow Climate Agreement quickly establishes rules and systems to reduce carbon emissions (UNFCCC 2021). This study focuses on South Asian economies (India, Pakistan, Nepal, Sri Lanka, and Bangladesh). The South Asian economies (SSE) are experiencing a higher level of economic expansion. For instance, India has the largest economic development, followed by Bangladesh, Pakistan, Nepal, and Sri Lanka. This increased economic growth requires energy, and currently, India's economy consumes the largest amount of power in the region (Sharma et al. 2021; Sohail et al. 2021). Shukla et al. (2017) noted that the SSE normally relies on traditional fossil fuels for their economic development activities, threatening environmental quality in this region. Although the SSE is progressing concerning economic development, these countries have not performed well in the sustainability of the environment (Sun et al. 2020). Therefore, it is imperative to analyze factors that affect ecological footprint (EFP) in these regions and provide a policy framework to help cure this menace.

The global average EFP per individual was approximately 2.75 hectares, and the global biocapacity was 1.63 hectares (Global Footprint Network 2018). This implies a shortage of 1.1 hectares of EFP globally (Sahoo & Sethi 2021). EFP as a surrogate measure for environmental pollution has recently emerged (Huang et al. 2022; Majeed & Mazhar 2020; Xu et al. 2022; Yang et al. 2021). The biocapacity (BIO) indicator is also considered an indispensable aspect of EFP. BIO can generate biological elements required by society and absorb waste emanated by human beings. Thus, BIO is measured yearly depending on the societal, economic system, climate change, and environmental management (Caglar et al. 2022). A situation whereby the level of EFP exceeds BIO due to rising demand by society from the ecosystem can lead to environmental pollution. BIO help accesses important information about the current nature capacity as the level of global EFP balance (Global Footprint Network (2018).

The concept of whether economic growth (EGC) causes EFP can be traced to the research conducted by (Grossman & Krueger 1995). Their research created an economic paradigm that asserted the link between economic growth and income disparity followed an inverted U-shape. Various literary works have tested this hypothesis from different nations and countries (Balsalobre-Lorente et al. 2019a, b; Danish & Wang 2019; Dong et al. 2017; Zhang 2021). EGC is generally measured with the gross domestic product (GDP) at a particular time. Countries normally require raw materials and capital to support their economic expansion mechanism. However, using these raw materials produces emissions that affect the environment. The inference is that various countries strive to develop their economies, and there is a likelihood of encountering EFP challenges.

The consumption of energy is irreplaceable material in the manufacturing and production process. Thus, the use of energy is a vital component in the economic growth of most countries. Therefore, most economies rely on traditional energy sources like coal, oil, fossil, and natural gas to meet energy demand. The continual consumption of these conventional energy affects the EFP (Murshed et al. 2021; Sunday et al. 2022). Moreover, exploring the interplay between EFP and green finance (GFN) has become a new topic of contention among ecological scientists. GFN as an investment plan for environmental conservation. As a result, GFN allows private investors to financially support green initiatives to fill the gap left by insufficient public expenditure (Muganyi et al. 2021). Navigating the effect of natural resource rent (NRR) on EFP is essential because, in the SSE, there is an abundance of natural resources that help in economic development. The utilization of NRR in an unsustainable manner can lead to a deficit in the EFP in most countries. Danish et al. (2020) observed that the exploitation of NRR increases due to higher economic expansion, which has negative consequences on environmental sustainability.

Another emerging concept related to environmental sustainability is using information and communication technology (ICT) for economic expansion. In today's world, ICT plays a vital part in improving people's well-being and promoting economic growth. Some studies suggest that the emergence of ICT has an inverse association with environmental pollution, and it improves environmental quality (Caglar et al. 2021; Haldar and Sethi 2022). Hence, analyzing the impact of ICT on EFP is key because of the increase in ICT development in the SSE. Agriculture value-added (AGRIC-VA) provides pivotal support and serves as a backbone to the EGC of most countries. Agricultural production is paramount in South Asian economic and social advancement. Thus, agriculture provides support to the improvement in EGC through the creation of employment avenues, food security, and provision of raw materials. Nevertheless, Pata (2021) argued that agricultural activities contributed



to almost 20% of global environmental pollution. Hence, it has become necessary to lessen the effect of agriculture practices on EFP. Moreover, the research by Rahman et al. (2021) indicated that by 2030, the reduction of emissions from agriculture methane would increase by 48%.

Considering the above discourse, the present research investigated the dynamic interplay between economic growth, biocapacity, renewable energy use, natural resource rent, agricultural value-added, green finance, ICT and ecological footprint. The critical question to answer in this study is how emerging economies like the SSE maintain environmental sustainability without compromising economic development. The research applied the environmental Kuznets curve (EKC) hypothesis to examine the interaction among the selected series to help answer this pressing question. The precritical contribution of this research is as follows; (1) Recognizing the complex relationship among variables that influence environmental sustainability can aid government and stakeholder development of strategies and procedures to address these issues. (2) Empirical evidence is critical in helping legislators, the citizenry, and various stakeholders better understand approaches to achieve environmental sustainability in the SSE. (3) The findings of this study will serve as a blueprint for emerging economies to develop economically and simultaneously improve the protection of the environment.

Theoretically, this research significantly contributes to environmental research in the following ways; (1) CO<sub>2</sub> is commonly used as a reference point for environmental pollution in a wide range of environmental studies, but this study used EFP to quantify environmental pollution. Extant studies have criticized the use of only CO<sub>2</sub> to quantify environmental pollution. This is because CO<sub>2</sub> emission covers only a nominal aspect of multifaceted environmental pollution confronting emerging countries (Majeed and Mazhar, 2020; Murshed et al. 2021; Suki et al. 2022; Udemba 2020). On the other hand, EFP can be described as a more holistic indicator of environmental contamination since it considers the human and industrial practices that contribute to an increase in the degradation of the environment (Suki et al. 2022). (2) The researchers are optimistic that this study is a pioneer in investigating variables such as green finance, natural resource rent, agriculture value-added, ICT, and EFP in emerging economies like the South Asia nations within the environmental Kuznets curve (EKC) hypothesis. Therefore, this study aims to fill a gap in the literature by providing empirical evidence on how these variables affect environmental pollution among the SSE. (3) This paper employed the newest second generational sectional dependence test (CSD) (Breitung 2001; Pesaran 2007). The study utilized three unique approaches proposed by (Kao 1999; Pedroni 2004; Westerlund 2007) to analyze the presence of long-term interactions among the series. The present study

further employed the cross-sectional-augmented autoregressive distributed lag (CS-ARDL) developed by Chudik and Pesaran (2015) to estimate the short and long-term estimators. This research also employed modern techniques, which include the common correlated effect means group estimator (CC-MG) and augmented mean group (AMG), proposed by Pesaran (2007) and Eberhardt and Bond (2009) as the robustness check to the CS-ARDL technique. Finally, the novel Dumitrescu and Hurlin (2012) was applied to analyze the causality connection between the series.

Apart from the introduction section, the rest of the paper is arranged as follows; Section two covers the literature review, Section three focuses on the methodology, data, and empirical model, Section four outlines the results and discussion, and Sect. 5 illustrates the conclusion and core policy framework.

## Literature review

This part of the study delves into the details of prior literary works on the nexus between economic growth, biocapacity, renewable energy use, natural resource rent, agricultural value-added, green finance, ICT and ecological footprint.

## Economic growth and ecological footprint nexus

EKC hypothesis was discovered in the research conducted by Grossman and Krueger (1995); the study analyzed the trade agreement's impact on environmental pollution in North America and revealed the presence of the EKC. This study has made an enormous contribution to literary works, and environmental scientists have adopted this theory in several research works, and they have reported mixed results concerning the EKC (Abid 2016; Balsalobre-lorente et al. 2019a, b; Saud et al. 2018; Suki et al. 2022; Zhang 2021). Uddin et al. (2017) investigated the link between EGC-EFP among 27 high emitters of CO<sub>2</sub> emissions with panel data from 1991 to 2012. Their findings indicated that EGC increases EFP. Similarly, Ahmed et al. (2019) analyzed the interplay between EGC-EFP in Malaysia using panel data from 1971 to 2014. Their empirical outcome revealed that EGC triggers EFP.

Akinsola et al. (2022) explored the effect of EGC-EFP on Brazil utilizing the CS-ARDL approach and data from 1983 to 2017. Their research findings revealed that EGC increases environmental pollution, and also, there exists a bidirectional interplay between EGC-EFP. In addition, Caglar et al. (2022) found that environmental pollution increases in the USA of America due to economic expansion. According to their findings, investment in renewable



energy is not at a level that can pass the turning point of EKC. Their study recommended that the US government invest more in renewable energy technologies and research and development. Islam (2022) also found out that EGC is a major determinant of environmental deterioration among the SSE. Their research indicated the existence of EKC among the SSE. The underlying reason for their study outcome was that quality and safety measures become obligatory in the economic sphere at the initial stage of economic development, helping to lessen EFP. However, research conducted by Caglar et al. (2021) did not validate the existence of EKC among the top ten emitters of EFP. The assumption behind their results was that EGC seems to be accompanied by EFP, and substituting a disreputable approach with a cleaner one is not working in these regions (Caglar et al. 2021).

### **Biocapacity and ecological footprint nexus**

BIO is an essential component of EFP because it encompasses biological activities such as croplands, fisheries, agricultural land, and forestry (Samargandi 2021). The issue of unsustainability comes to mind when the level of EFP is higher than BIO. Many countries in the world are confronted with an EFP deficit due to over-dependence on natural resources beyond the proliferative potential of BIO (Danish et al. 2020; Rashid et al. 2018). Unal and Aktug (2022) have analyzed the interplay between BIO and EFP among the G20 economies employing data from 1970 to 2016. According to their findings, there is a direct interaction between BIO and ecological footprint. In addition, Agbede et al. (2021) evaluated the relationship between BIO and EFP and applied the CS-ARDL methodology with panel data spanning from 1971 to 2017. Their study showed a positive and bidirectional causality association between BIO and EFP. Sarkodie and Strezov (2018) also found a unidirectional interaction running from EGC to BIO and a bidirectional association between EFP and BIO. Tauseef et al. (2019) confirmed that biocapacity activities cause an upsurge in environmental pollution in Pakistan.

### **Renewable energy use and ecological footprint nexus**

Environmental research has widely recognized the interaction between REU and EFP. REU is thought to help with environmental pollution and energy security policies. Industries seek to increase productivity and profitability with less waste production by utilizing REU for manufacturing and production purposes, lowering EFP (Doğan et al. 2021).

Empirical findings by Agbede et al. (2021) have indicated that REU plays a significant role in EGC, affecting environmental pollution. Suki et al. (2022) evaluated the association between REU, EGC, and ecological sustainability in Malaysia. Their findings demonstrated that REU enhances the reduction of pollution levels in the environment. Similarly, Nguyen and Kakinaka (2019) evaluated the association between REU and pollution in regions at various stages of economic growth. Their study used panel co-integration tests on a dataset extending 107 economies from 1990 to 2013. Their analyses indicated that regions with low-income economies positively correlate with REU and EFP. On the other hand, high-income countries had an inverse relationship between REU and carbon emissions. Another study conducted by Murshed et al. (2021) among the SSE indicated that REU decreases the effect of ecological footprint in these regions. Likewise, extensive literature works have found convincing evidence demonstrating that REU reduces the level of EFP in various countries (Akinsola et al. 2022; Usman and Makhdam 2021).

### **Green finance and ecological footprint nexus**

GFN and ecological sustainability has gained significant prominence in environmental policy and research. GFN is a broad concept that focuses on economic investment tailored toward sustainability initiatives and practices supporting ecological integrity (Nawaz et al. 2021). GFN lessens environmental deterioration based on the assumption that GFN stimulates investments into advanced technologies by large companies, for example (non-fossil innovation investment), which promotes environmental quality (Wang et al. 2021). Notwithstanding, research concerning the interaction between GFN and EFP is still being explored. Saeed Meo and Karim (2021) assessed the effects of GFN on environmental conservation in the top ten GFN-investing economies. According to their findings, GFN has an indirect relationship with EFP. Their research proposed that GFN is an effective strategy for enhancing environmental sustainability. Guild (2020) discovered that GFN has a strong relationship with environmental sustainability in Indonesia. Wang et al. (2021) found that GFN interacts negatively with EFP. According to their findings, GFN is the best financial investment for improving EFP.

### **Natural resource rent and ecological footprint nexus**

Recently, the interplay between NRR and EFP has been investigated by environmental scientists. For instance, Ahmad et al. (2020) scrutinized the interaction between NRR and EFP among emerging economies employing data



from 1984 to 2016. Their research findings stressed the higher exploitation of NRR enhances environmental deterioration. Nevertheless, modern technological innovation in exploiting natural resources can be the best alternative for mitigating the positive effect of NRR on EFP. Likewise, Erdogan et al. (2021) argued that the over-dependence of sub-Saharan African economies on NRR for economic expansion increases environmental pollution. Razzaq et al. (2020) believe that the depletion of NRR leads higher level of environmental degradation in the USA. Ibrahim and Ajide (2021) indicated that NRR, financial development, and regulatory quality contributed to EFP in Brazil, Russia, India, China, and South Africa (BRICS) economies. In addition, Kongbuamai et al. (2020) indicated that environmental sustainability could be achieved through the proper harnessing of NRR.

### Agriculture value-added and ecological footprint nexus

Notable environmental studies have examined the effect of agriculture value-added (AGRIC-VA) on EFP by employing different econometric approaches. Pata (2021) dissected the relationship between the impact of agriculture on EFP among the BRICS countries. Their research revealed a positive and bidirectional interaction between AGRIC-VA and EFP. Balsalobre-Lorente et al. (2019a, b) concluded that AGRIC-VA activities put a lot of pressure on the ecological system. Their analysis also indicated a unidirectional association between them AGRIC-VA and EFP. Udemba (2020) suggested that agriculture activities contribute to environmental pollution in India. The research argued that agriculture activities, including fishing, rearing, and farming, constitute the dominant source of employment in this region. Most of these agriculture activities involve using chemicals, fertilizers, and weedicides for higher crop yield, which affect EFP. Qiao et al. (2019) also explored the interplay between AGRIC-VA, REU, EGC, and environmental pollution from 1990 to 2014 among the G20 economies. Their findings revealed that agriculture activities escalate ecological breakdown in the long-term in these economies. Employing the quantile regression approach, Salari et al. (2021) probed into the interplay between REU, globalization, AGRIC-VA, and EFP from 2002 to 2016. Their research findings showed that AGRIC-VA increases the level of EFP in emerging countries. However, Ben Jebli and Ben Youssef (2019) applied the ARDL methodology and found that AGRIC-VA dissipates environmental degradation in Brazil. Alvarado et al. (2021) argued that AGRIC-VA positively impacts EFP and air quality.

### ICT and ecological footprint nexus

Over the last few decades, the ICT industry has been very competitive, and the amount of data used by businesses, governments, and consumers has increased exponentially. According to Fryer (2019), the mechanism through which ICT can help dissipate environmental pollution is dual; (1) ICT can reduce environmental pollution through renewable uptakes and energy efficiency. (2) ICT can reduce emissions from a wider economic perspective. Environmental researchers have indicated contradicting results regarding the interaction of ICT and EFP. Some studies have reported that ICT requires a lot of energy to function properly and efficiently, contributing to higher EFP levels. For instance (Raheem et al. 2019) among G7 regions, (Asongu et al. 2018) among sub-Saharan regions, and (Shabani and Shahnazi 2019) in Iran all reported a positive association between ICT and environmental pollution. In contrast, extant studies have also demonstrated that ICT can be a critical tool for enhancing environmental sustainability. For example, Kahouli et al. (2022) discovered that ICT has an inverse association with EFP in Saudi Arabia. In addition, Ozpolat (2021) applied the AMG techniques to evaluate the interaction between internet use and EFP among the G7 economies from 1990 to 2015. According to their findings, the use of the internet does not significantly affect EFP in these regions. Likewise, Khan et al. (2018) probed the interplay between ICT and ecological pollution from OECD economies. The authors reported that ICT does not destroy environmental quality.

## Materials and methods

### Theoretical underpinning

The environmental Kuznets curve assumes that EGC is a deterrent to environmental quality but that improving it will reduce pollution (Xiaoman et al. 2021). Furthermore, as a result of improvement in the economic development of the SSE, the demand for resources from people increases daily which require higher energy demand. This continuous demand for goods and services leads to the depletion of resources, which impacts the environment. As per the ECK theory and studies from environmental scientists, it has been established that the nexus between EGC and environmental pollution is endogenous; thus, "it first increases and then reduces" (Majeed and Mazhar 2020; Murshed et al. 2021; Zhang 2021). Hence, the present research used EGC and the quadratic term  $(EGC)^2$  to assess the presence of ECK in the South Asian economies. This study expects a U-shaped ECK hypothesis in the SSE economy. Economic growth (EGC)

was measured in terms of gross domestic product annual performance from one year to another. The baseline for the evaluation of EGC is per capita (constant \$2,010) for all the selected countries analyzed in this research (WID 2022).

Wackernagel and Rees (1998) proposed the environmental footprint concept; their study proposed that EFP covered different components of environmental pollution-related issues. Thus, EFP comprises six key elements: cropland, grazing lands, forest products, carbon, built-up land, and fishing grounds, as depicted in Fig. 1.

The interplay between EFP and BIO is essential because BIO plays an indispensable role in the ecological system. Shujah-ur-Rahman et al. (2019) stressed that BIO has a dual effect (thus, BIO serves as the production of biological materials and helps absorb GHG emissions). A study conducted by Ulucak and Bilgili (2018) argued that BIO is a major predictor of EFP in middle- and low-income economies. Hence, the researchers expect BIO to impact EFP positively in this research. REU components such as biofuel, wind, hydro-power, and biomass have been identified by environmental scientists as better alternative energy sources than traditional sources such as fossil fuels (Adebayo et al. 2021; Caglar et al. 2021). Musah et al. (2020) stated that an increase in efficiency in a country's REU impacts EFP. As a result, the present research expects an inverse relationship between REU and EFP in the SSE. GFN plays a pivotal role in most countries' environmental sustainability and economic growth. To content with an environmental scientist, GFN was introduced with the concept that collaboration exists between government and the private sector to initiate actions that can incorporate technological development, innovation, and the protection of the environment through green initiatives (Smith 2019). With the increase in EFP in the SSE, the role of GFN is essential. Hence, this study predicts that GFN will have an inverse association with EFP.

The over-exploitation of NRR has serious environmental repercussions. NRR is regarded as a cleaner energy source that balances the pressure on natural resources (Tobelmann & Wendler 2019). Tufail et al. (2021) assert that economic growth forces many countries to exploit available NRR inefficiently, resulting in land degradation and EFP. As a result, this study argues that increasing the use of NRR without detailed oversight can positively impact the level of EFP in the SSE. Therefore, this study anticipates a direct and positive interaction between NRR and EFP. As suggested by previous researchers, agriculture value-added (AGRIC-VA) contributes to the high level of environmental pollution. Pata (2021) concluded that AGRIC-VA produces waste materials that pollute rivers, soil, and ecosystems. Moreover, since



**Fig. 1** Graphical illustration of the components of ecological footprint. (Source: Author's own)

farmers in the SSE use more fossil energy sources for their agricultural production, which contributes to higher emissions in the environment, hence in this study this research asserts that AGRIC-VA will have positive interaction with EFP.

The effect of ICT on EFP is inconclusive in the literature. Some researchers argue that the efficient utilization of ICT can help improve the quality of life and society (Caglar et al. 2021; Raheem et al. 2019). In contrast, extant studies have also indicated that the uprise in ICT usage, which requires energy, can adversely affect the environment (Kahouli et al. (2022). Diaz-Roldán and Ramos-Herrera (2021) proved that ICT enhances EGC but has a mitigating impact on environmental degradation. The present study expects the use of ICT to help in mitigating EFP in the SSE.

Based on the EKC theory and consistent with previous literary work by Haldar and Sethi (2022), this study's econometric approach is mathematically expressed as in Eq. (1):

$$EFP^{it} = f(EGC^{it}, EGC^{2it}, BIO^{it}, REU^{it}, GFN^{it}, NRR^{it}, AGRIC - VA^{it}, ICT^{it}) \tag{1}$$

All selected variables were transformed to the natural logarithm for better distribution and sharpness among the data series. The natural logarithm transformation of the series aids in the resolution of heteroskedasticity and autocorrelation issues in the study data. The log-linear form of the EFP is expressed in Eq. (2)

$$\begin{aligned} \ln EFP^{it} = & \phi_0 + \phi_1 \ln EGC^{it} + \phi_2 \ln EGC^{2it} \\ & + \phi_3 \ln BIO^{it} + \phi_4 \ln REU^{it} \\ & + \phi_5 \ln GFN^{it} + \phi_6 \ln NRR^{it} \\ & + \phi_7 \ln AGRIC - VA^{it} \\ & + \phi_8 \ln ICT^{it} + \epsilon^{it} \end{aligned} \tag{2}$$

Such that  $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7$  and  $\phi_8$  are the coefficient of economic growth (EGC), square root of economic development (EGC)<sup>2</sup>, biocapacity (BIO), renewable energy use (REU), natural resource rent (NRR), agricultural value-added (AGRIC-VA), green finance (GFN), Information Communication and Technology (ICT) and ecological footprint (EFP). *ln* denotes the series natural logarithm form,  $\phi_0$  is the constant in the model,  $\epsilon$  represents the error terms of the model. Also, *i* represents cross sections (India, Pakistan, Nepal, Sri Lanka, and Bangladesh), and *t* indicates the time of the study (1990 to 2017).

### Description of variables and source of data

The panel data for ecological footprint and biocapacity were derived from (Global Footprint Network 2018). Green finance indicators were generated from the (OECD 2022) database. The data for renewable energy use, natural resource rent, agricultural value-added, and Information Communication and ICT were derived from the world development indicators (WID 2022). Table 1 indicates the unit

of measurement, symbols, and data sources for the selected series (Table 2).

### Descriptive statistical information

Table 3 provides descriptive, correlation and variance inflation factor (VIF) analysis for the series under consideration in this study. The outcome indicates the mean statistics for EFP (0.881), BIO (0.431), EGC (25.356), NRR (0.371), REU (4.058), GFN (2.121), AGRIC-VA (6.991), and ICT (14.329). These results infer that a significant difference exists among the SSE in all the series examined in this study. Also, the study results show a comparatively high standard deviation among the selected series. More specifically, EFP (0.229), BIO (0.063), EGC (25.356) NRR (0.960), REU (0.277), GFN (0.754), AGRIC-VA (0.612) and ICT (1.730). The implication of these results shows that there is a high possibility of the presence of heterogeneity across the variable analyzed in this study. The data structure's normality was also examined using statistics such as kurtosis, Jarque–Bera, and probability tests which also proved that the study data sample is not normally distributed. Table 3 further provides the outcome of the bivariate correlation analysis. The results indicate that EFP is positively correlated with BIO, EGC, and ICT. In addition, NRR, REU, GFN, and AGRIC-VA are inversely correlated with EFP. This result shows that all series are also modestly associated with EFP. Finally, to analyze the issue of multicollinearity in this research, the study applied the variance inflation test. As indicated in Table 3, the results show that the study model lacks multicollinearity since both the mean and individual VIF estimates are less than 10, as suggested by Nathaniel et al. (2021). The comparison of trend analysis of all the series is indicated in Figs. 2, 3, 4, 5, 6, 7, 8.

**Table 1** Description of variables and source of data

Variable	Symbol	Description	Source
Ecological footprint	EFP	Per capita of global hectare	(Global Footprint Network, 2018)
Biocapacity	BIO	Per capita of global hectare	(Global Footprint Network, 2018)
Economic growth	EGC	Per capita (constant \$2010)	
Renewable energy use	REU	Per capita of energy use (kg of oil)	(WID, 2022)
Green finance	GFN	Environmental protection products by residents	(OECD, 2022)
Natural Resource Rent	NRR	Natural resource rent % GDP	(WID, 2022)
Agricultural value-added	AGRIC-VA	Agriculture, forestry, and fishing, value-added (constant 2015 US\$)	(WID, 2022)
Information, communication and technology	ICT	Population % of individuals using internet	(WID, 2022)

**Table 2** Synopsis of descriptive statistical information

Descriptive Statistics	EFP	BIO	EGC	NRR	REU	GFN	AGRIC_VA	ICT
Mean	0.881	0.431	25.356	0.371	4.058	2.121	6.991	14.329
Median	0.834	0.427	25.302	0.113	4.033	2.097	7.013	14.006
Max	1.540	0.578	28.518	1.960	4.555	4.605	7.948	17.731
Min	0.443	0.315	22.836	-2.343	3.453	0.029	5.944	10.956
Std dev	0.229	0.063	1.473	0.960	0.277	0.754	0.612	1.730
Skewness	0.557	0.373	0.320	-0.580	0.092	0.585	-0.118	0.248
Kurtosis	3.444	2.423	2.294	2.678	2.318	4.108	1.715	2.331
Jarque-Bera	8.4164	5.200	5.306	8.453	2.907	15.161	9.944	4.045
Prob	0.000***	0.007***	0.000***	0.000***	0.001***	0.000***	0.000***	0.000***
Observation	140	140	140	140	140	140	140	140
<i>Correlation analysis</i>								
EFP	1.000							
BIO	0.496	1.000						
EGC	0.035	0.548	1.000					
REU	-0.066	0.659	-0.848	1.000				
NRR	-0.273	-0.031	0.512	-0.254	1.000			
GFN	0.026	0.146	-0.238	0.272	-0.552	1.000		
AGRIC-VA	0.499	-0.276	0.465	-0.613	-0.127	-0.010	1.000	
ICT	0.146	-0.124	0.809	-0.535	0.682	-0.247	0.281	1.000
<i>Variance inflation factor analysis (VIF)</i>								
		VIF			1/VIF			VIF mean
BIO		4.429			0.225			3.864
EGC		5.801			0.172			
REU		3.742			0.267			
NRR		2.640			0.378			
GFN		4.665			0.214			
AGRIC-VA		5.871			0.170			
ICT		2.540			0.393			

**Table 3** Synopsis of the CSD results

Series	Breusch-Pagan LM	Pesaran scaled LM	Bias-Cor- rected Scaled LM
InEFP	158.450***	33.194***	33.101***
InBIO	39.857***	6.6762***	6.583***
InEGC	277.813***	59.884***	59.792***
In(EGC)2	277.825***	59.887***	59.795***
InREU	228.3003***	48.813***	48.720***
InNRR	95.884***	19.204***	19.111***
InGFN	59.636***	11.098***	11.006***
InAGRIC-VA	154.257***	32.257***	32.164***
ICT	231.313***	49.487***	49.394***
<i>H0: slope coefficient is homogenous</i>			
$\Delta$	P-Stats	$\Delta$ Adjusted	P-stats
12.429	0.000***	9.2160	0.000***

Note: 1% denotes the level of significance





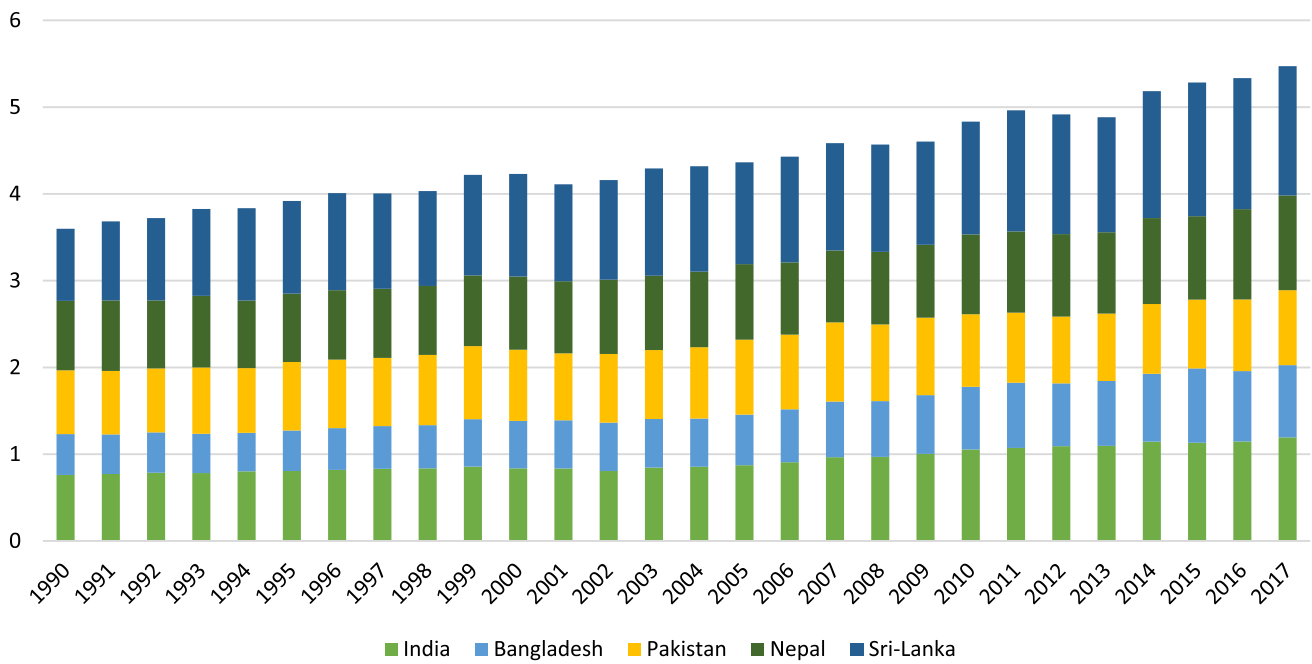


Fig. 2 Trend comparison of South Asian countries' ecological footprint from 1990 to 2017

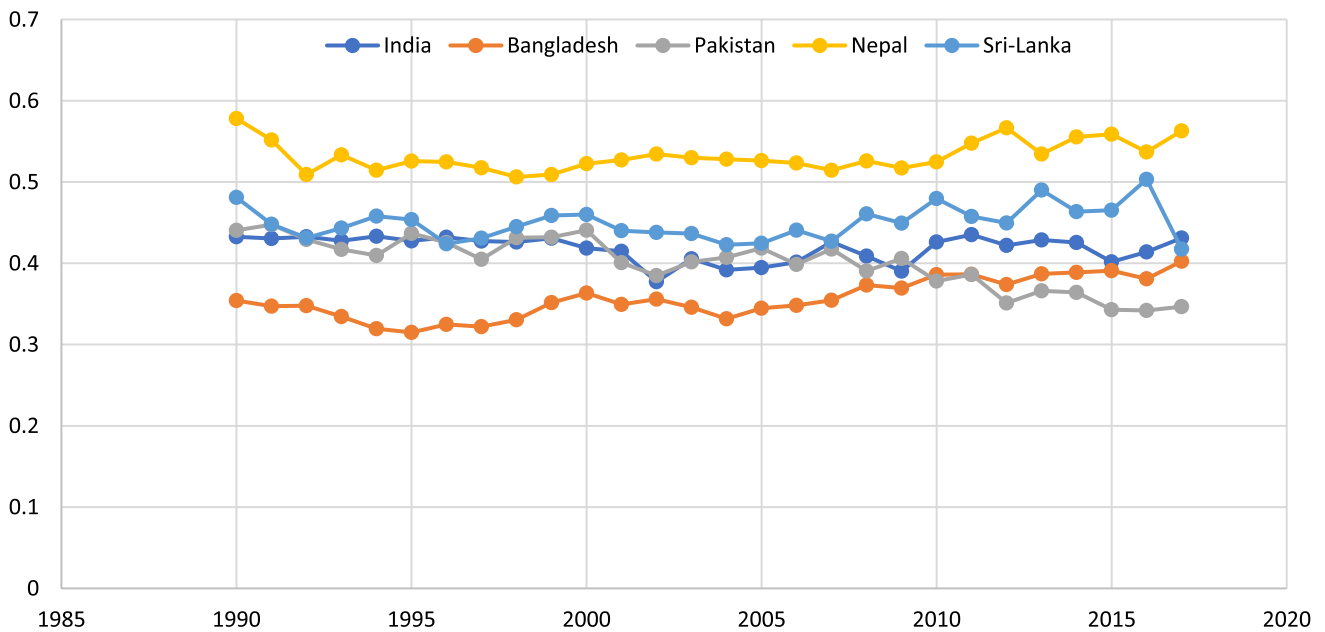


Fig. 3 Trend comparison of South Asian countries' biocapacity from 1990 to 2017

**Econometrics approach**

**Coefficient of slope homogeneity test and cross-sectional dependency test**

This research examines the slope homogeneity test (SHT) since the disregard of this test may raise the concern of estimating inaccurate and distorted predictions (Mohanty

and Sethi, 2021). Hence, this research applied the Pesaran and Yamagata (2008) slope homogeneity test. The SHT and adjusted SHT is mathematically expressed in Eq. 3 and 4 as:

$$\tilde{\Delta}SHT = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}} \left( \frac{1}{N} \tilde{S} - K \right) \tag{2}$$

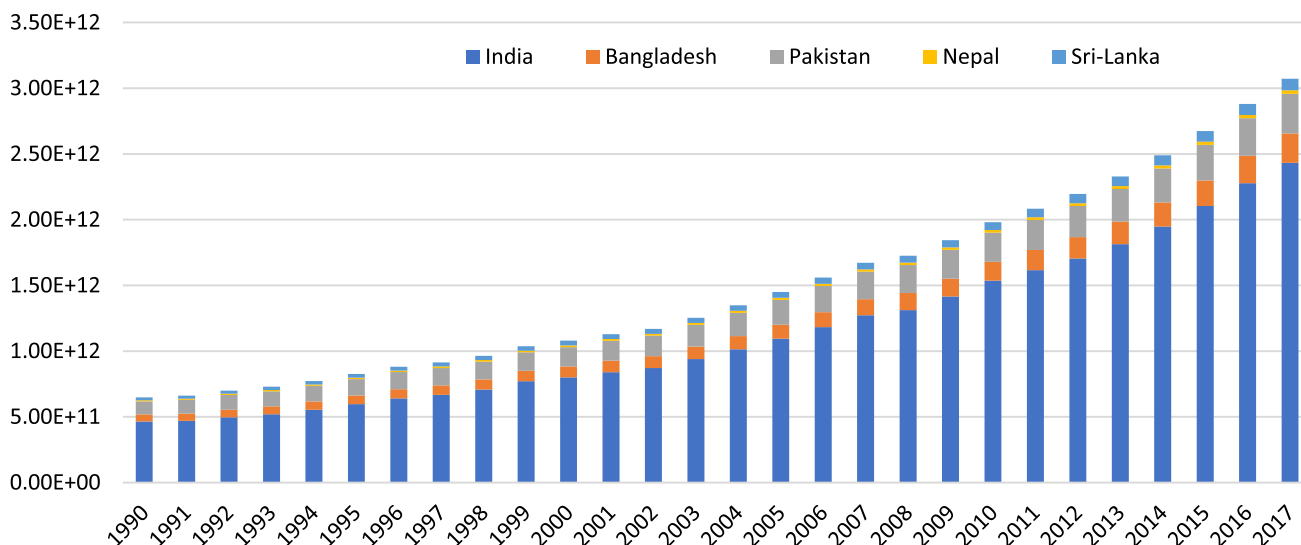
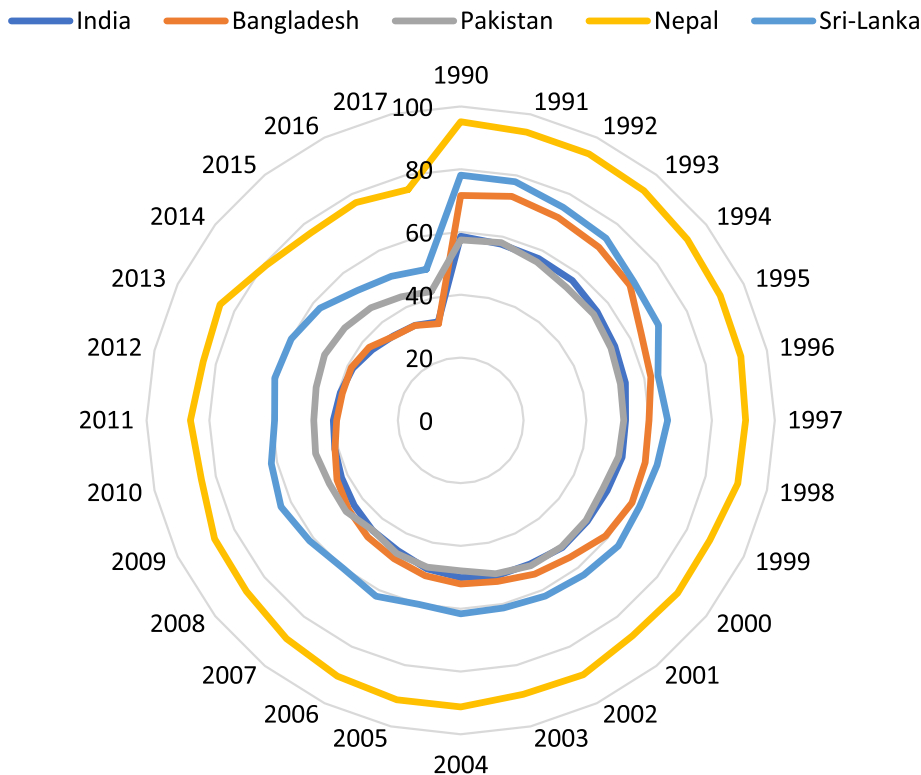


Fig. 4 Trend comparison of South Asian countries' economic growth from 1990 to 2017

Fig. 5 Trend comparison of South Asian countries' renewable energy use from 1990 to 2017



$$\tilde{\Delta}ASHT = (N)^{\frac{1}{2}} \left( \left( \frac{2k(T-k-1)}{T+1} \right)^{\frac{-1}{2}} \right) \left( \frac{1}{N} \tilde{S} - K \right) \quad (3)$$

Such that  $\tilde{\Delta}SHT$  denotes the delta SHT and  $\tilde{\Delta}ASHT$  represents adjusted SHT, respectively.

Furthermore, cross-sectional dependency (CSD) might lead to inefficiency and unpredictability in the assessed

parameters. As a result, these complications could arise due to various causes, including common disturbances, geographical effects, and unanticipated country-specific elements. Thus, testing the CSD among the variables is important because it helps overcome inconsistent results and bias (Mohanty and Sethi 2021). Therefore, this research applied the following CSD test (Breusch and Pagan 1980) and (Chudik and Pesaran 2015; Pesaran 2007). The

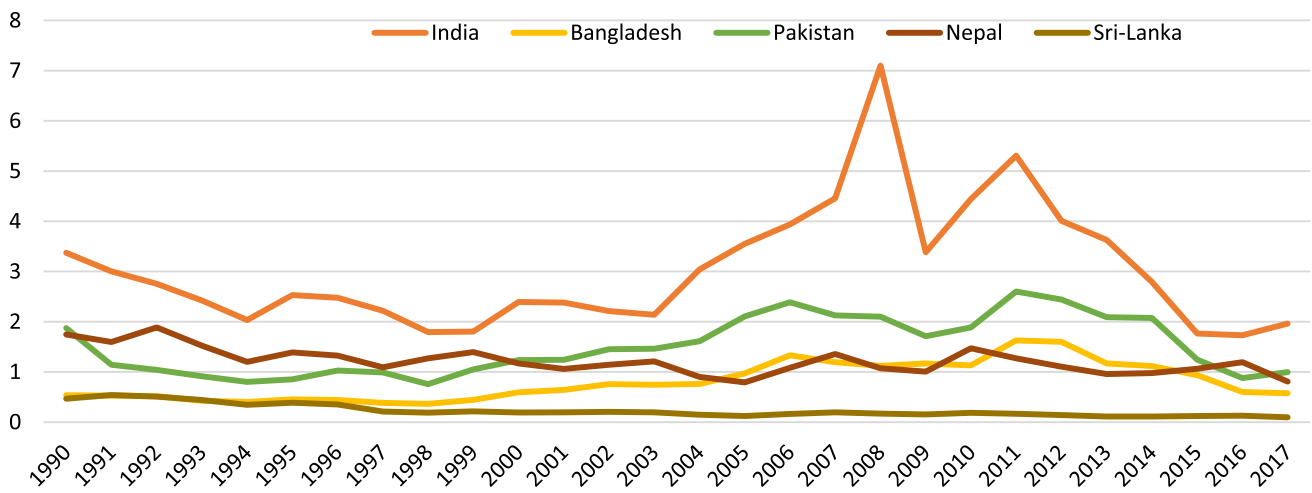


Fig. 6 Trend comparison of South Asian countries' natural resource rent from 1990 to 2017

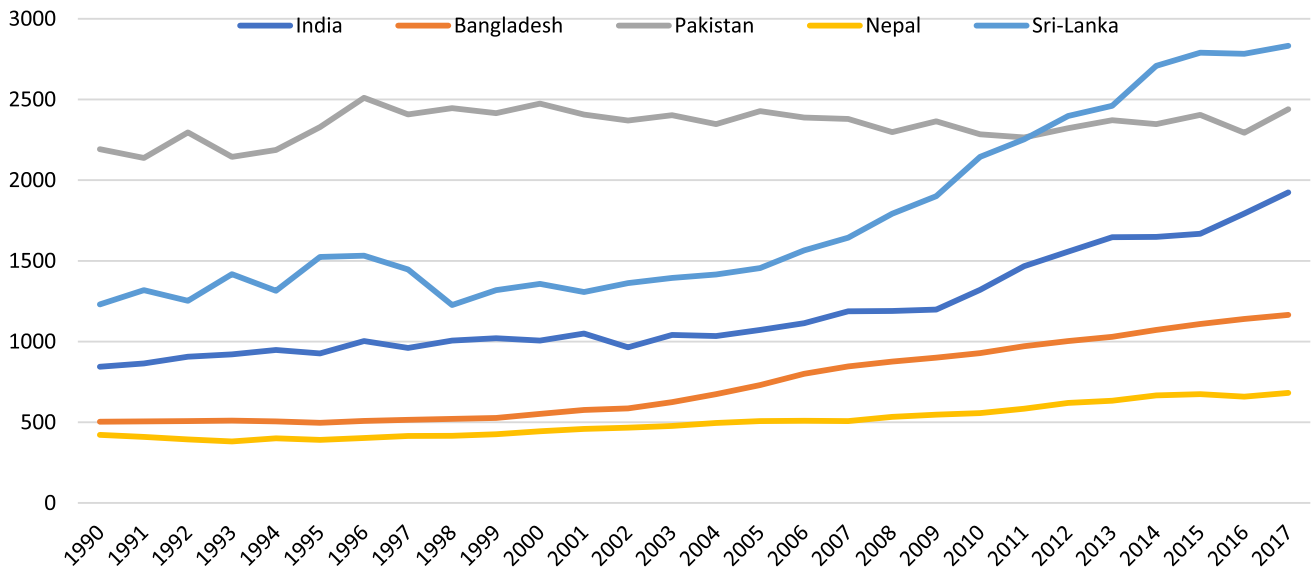


Fig. 7 Trend comparison of South Asian countries' agriculture value-added from 1990 to 2017

mathematical representation of Chudik and Pesaran (2015) is shown in Eq. (5):

$$CSD \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^N \varphi_i \sum_{m=i+1}^N \partial_{im} \tag{5}$$

Such that T indicates the time, N represents the CSD in the panel,  $\partial_{ij}$  denotes the correlation coefficient of i and m units.

**Unit root tests**

The study applied the second-generation panel root test, i.e., Cross-sectional Augmented Dickey–Fuller (CADF)

and Cross-sectional I'm Pesaran and Shin (CIPS), to examine the stationarity among the variables. The CADF and CIPS test assist in addressing the issues of CSD and also tackle spurious in analyzing regression results. Moreover, both stationarity tests helped the researchers examine the robustness and accuracy of the series heterogeneity. The mathematical expression for the CADF test is described below in Eq. (6):

$$\Delta x_{it} = \alpha_{it} + \beta_{it-1} + \delta_i T + \sum_{j=1}^N \gamma_{ij} \Delta x_{it-j} + \mu_{it} \tag{6}$$

Such that  $x_{it}$  indicates the variables analyzed in the study,  $\Delta$  represents the difference in the variables,  $\mu_{it}$  shows the white error term.

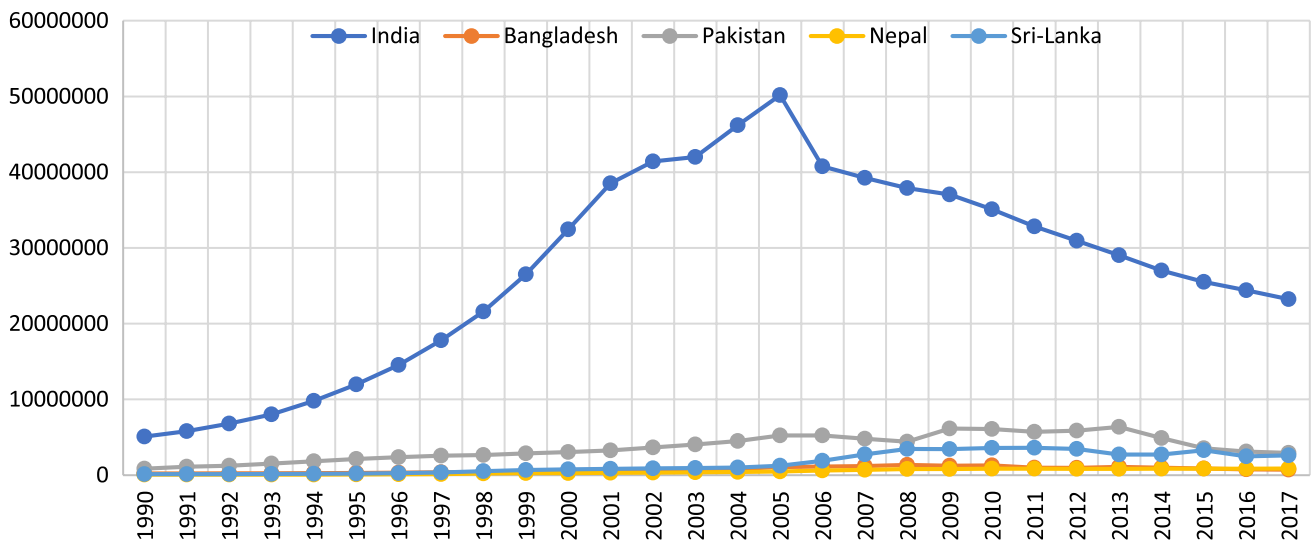


Fig. 8 Trend comparison of South Asian countries' ICT usage from 1990 to 2017

The CIPS test is expressed in a mathematical form as in Eq. (7):

$$CIPS = \frac{1}{N} \sum_{i=1}^N \varphi_i(N, T) \tag{7}$$

Such that the parameter  $\varphi_i(N, T)$  indicates CADF regression test statistics.

**Panel co-integration test**

The Pedroni (2004) co-integration approach explores the co-integration association between the series by examining if the residual value component of the equation is steady. The null hypothesis ( $H_0$ ) of this technique is that there exists no co-integration in the series. (Pedroni 2004) co-integration test is expressed mathematically as in Eq. (8):

$$Y_{it} = \alpha_i + \psi_i t + \sum_{n=0}^N \beta_{ni} X_{nit} + \mu_{it} \tag{8}$$

Such that  $\alpha_i$  indicates the specific-individual effect,  $\psi_i t$  shows the series trend, and  $n$  represents the explanatory variables. This research also used the Westerlund (2007) co-integration approach to analyze the CSD and heterogeneity in the research series. The null hypothesis ( $H_0$ ) of this technique indicates that there exists no co-integration in the error-correction term among the series. The model is mathematically expressed as in Eq. (9):

$$\begin{aligned} \Delta Y_{it} = & \psi_i d_t + \alpha_i (Y_{it-1} - \beta_i X_{it-1}) \\ & + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{it-j} + \sum_{j=-p_i}^{p_i} \phi_{ij} \Delta X_{i,t-j} + \mu_{it} \end{aligned} \tag{9}$$

Such that  $d_t = (1, t)'$  provides the series trend, elasticity estimates  $\psi_i = \psi_1$  and  $\psi_2$  indicates the constant term for all countries series, and  $i$  and  $t$  indicate all the CSD and period of the study. The test statistics of the two categories of this approach are expressed mathematically as in Eqs. (10–13):

$$G_\tau = \frac{1}{N} \sum_{i=1}^N \frac{\eta_i}{S.E(\hat{\eta}_i)} \tag{10}$$

$$G_a = \frac{1}{N} \sum_{i=1}^N \frac{T\eta_i}{1 - \sum_{j=1}^k \hat{\eta}_{ij}} \tag{11}$$

The panel co-integration approach statistics is mathematically estimated as

$$P_\tau = \frac{\hat{\eta}_i}{S.E(\hat{\eta}_i)} \tag{12}$$

$$P_a = T\eta_i \tag{13}$$

Such that  $G_\tau$  and  $G_a$  shows the group mean statistics,  $P_\tau$  and  $P_a$  indicates the panel statistics  $\hat{\eta}_i$  indicates the transition from short to long-term equilibrium in terms of speed.

### Long-run estimation models

The research employed the CS-ARDL espoused by Chudik and Pesaran (2015) to analyze the short and long-term estimators. Compared with other estimation approaches, such as the pooled mean group (PMG), the performance of this approach (CS-ARDL) provides better results, and the estimates are robust. Also, CS-ARDL techniques help solve heteroscedasticity, endogeneity, and serial correlation (Baydoun and Aga, 2021; Huang et al. 2021). The mathematical expression of the CS-ARDL is as indicated in Eq. (14)

$$\Delta EVQ_{i,t} = \delta_i + \sum_{j=1}^m \delta_{it} EVQ_{i,t-j} + \sum_{j=0}^m \delta'_{it} X_{i,t-j} + \sum_{j=0}^1 \delta'_{it} \bar{Z}_{i,t-j} + \mu_{it} \tag{14}$$

Such that the average for the cross sections is represented by  $\bar{Z}_i = (\Delta EVQ_{i,t}, \bar{X}_i)'$  Where  $X$  indicates the explanatory series in the model, which include EGC, REU, GFN, NRR, ENI, and URB.

### Robustness test

This study further used the AMG and CC-MG, as suggested by Eberhardt and Bond (2009), to analyze the robustness of short and long-term estimates in the research. The AMG and CC-MG model applies to this research because it is robust and helps derive unbiased and accurate estimates. The AMG technique is based on a two-stage approach and is mathematically expressed as in Eqs. (15–16):

Stage one AMG technique:

$$\Delta Y_{it} = \varphi_i + \delta_i \delta X_{it} + \gamma_i \vartheta_t + \sum_{t=2}^T \theta_i \Delta D_t + \mu_{it} \tag{15}$$

Stage two of the AMG technique:

$$AMG_{Estimator} = N^{-1} \sum_{i=1}^N \hat{\beta}_i \tag{16}$$

Such that  $\varphi_i$  represent the intercept,  $Y_{it}$  and  $X_{it}$  indicates the observed variable,  $\vartheta_t$  denotes heterogenous variables with unobserved common factors,  $\Delta$  indicates the initial operator of the variables,  $\theta_i$  illustrates the dummy conditions associated with the time dimension  $t$ , and  $\mu_{it}$  represents the model's stochastic error term. The CC-MG considers the serial correlation among the series, the robustness of a non-cointegrated structural flaw, and unexplained common elements (Kapetanios et al. 2011). The CC-MG is expressed mathematically in Eq. (17):

$$Y_{it} = \alpha_{1i} + \beta_i X_{it} + \theta_i n_{it} + \mu_{it} \tag{17}$$

Such that  $Y_{it}$  and  $X_{it}$  indicate as observed variables,  $\alpha_{1i}$  indicate the specific group effect,  $\beta_i$  represents the

cross-sectional estimators' slope,  $n_i$  shows the unknown common factor with loading with  $\theta_i$  heterogenous and  $\mu_{it}$  exhibits the model's stochastic error term. The augmented model with a mean cross section of the explained and unexplained variables can be expressed as in Eq. (18):

$$Y_{it} = \alpha_{1i} + \beta_i Z_{it} + \varphi_i \bar{y}_{it} + \bar{z}_{it} + \theta_i n_{it} + \mu_{it} \tag{18}$$

This regression was calculated using the ordinary least square technique for each cross section. To estimate the country-wise coefficient estimators' Eq. 18 offers a robust outcome, and it is mathematically expressed as in Eq. (19):

$$CCMG = N^{-1} \sum_{i=1}^N \hat{\theta}_i \tag{19}$$

### Causality analysis

The research employed the modern granger causality test Dumitrescu and Hurlin (2012) to investigate the dynamic linkages between series. This approach helps address the possibility of CSD and whether there is slope variability in the research model. The null hypothesis of the Dumitrescu and Hurlin (D-H) granger causality test is that the variables have no causal association. In contrast, the alternative hypothesis is a causal relationship in the model. The D-H non-causality test is expressed mathematically expressed in Eq. (20):

$$Y_{it} = \alpha_i + \sum_{m=1}^M \psi_i^m Y_{i(m-t)} + \sum_{m=1}^M \lambda_i^m Z_{i(m-t)} \tag{20}$$

Such that  $m$  indicates the length of the lag,  $\psi_i^m$  shows the autoregressive parameters of the model.

## Results and discussion

### CSD and SHT test outcome

This research employed three CSD tests to analyze cross-sectional dependence among the selected series. The outcome of the CSD test is presented in Table 3. At a significance level of 1%, the test results confirm the rejection of the null hypothesis of CSD presence among the variables' cross section. As a result, this analysis can conclude that the South Asian economies are interconnected in economic development, ICT, agriculture, natural resource, and ICT developments. The next step in the study's model is to analyze the level of stationarity among the series examined in

this study. Table 3 further shows the slope homogeneity test results, which indicate that the null hypothesis of the SHT is rejected for the SSE, indicating that heterogeneity exists. Furthermore, the results suggest that the method for estimating the CSD and heterogeneity in the next stages of the research is feasible.

**Panel stationarity test**

After addressing the issue of CSD among the research series, it is important to test the stationarity level and the integration order among the series. In panel pane data analysis, it is critical to analyze the stationarity among the variable. As indicated by extant literature, the non-stationarity of the research data can lead to flawed and incoherent results (Huang et al. 2022; Yang et al. 2021). This research applied two newest second-generation unit root tests, namely; CADF and CIPS, to examine the stationarity among the series. None of the series (InEFP InBIO InEGC InNRR, InREU InGFN InAGRIC-VA InICT) was stationary at level, as shown in Table 5. However, after the first difference, the series of all candidates became stationary (1). This procedure can determine whether or not the series used in this study have long-term co-integration.

Table 4. shows synopsis of unit root test.

**Co-integration analysis**

This research utilized three co-integration procedures to establish the presence of long-term co-integration interaction among the series in this study. Table 5 displays the results of the co-integration test. The result of the co-integration test is shown in Table 5. Seven of the eleven analytical outcomes of the Pedroni (2004) co-integration test reject the null hypothesis, implying that the candidate series are not cointegrated. The outcome demonstrates that

the research model's variables have a co-integration interaction. The Westerlund (2007) co-integration approach uses two criteria and two-panel statistics to value their potential outcomes. Table 5 shows that both classifications ( $G_t$  and  $G_a$ ) are statistically relevant, with a highly significant level of 1%. Furthermore, Kao's co-integration outcome confirms a long-term co-integration among the selected series.

**Long-run elasticity estimation**

This study estimated the magnitude of this short and long-term interaction by incorporating novel approaches, such as the CS-ARDL, applied in previous studies (Alper et al. 2022; Caglar et al. 2022; Wang et al. 2020). The results for the short and long-term estimates are indicated in Table 6.

The shape of the ECK hypothesis was initially verified by analyzing the turning point. Among the SSE, the presence of the EKC occurs between \$413 and \$ 10,538 at a turning point of \$ 8,712. This outcome suggests that economic growth increases EFP before reaching the turning point (\$ 8,712). Moreover, as provided in Table 6, the empirical result indicates that the coefficient of economic growth is positive, and the square of economic growth is inversely related to EFP. This result confirms the EKC hypothesis for the South Asian economies. The findings indicate the existence of an inverted U-shape of the EKC hypothesis, which implies that the economic growth contributes to the environmental pollution at the initial stages; however, after moving the specific threshold, it tends to decline (Grossman and Krueger 1995). Moreover, Muhammad Awais Baloch et al. (2021) indicated that economies generally require more energy to enhance growth in the initial phases of economic expansion. These countries use typically obsolete technology for their production process, thereby escalating EFP. This outcome is in-line with

**Table 4** Synopsis of unit root test

Series	CADF		CIPS		Order of integration I(1)
	Level	First difference	Level	First difference	
InEFP	1.729	-3.570***	0.759	-6.399***	I(1)
InBIO	-0.302	-3.591***	-1.214	-5.534***	I(1)
InEGC	-0.293	-6.342***	-0.583	-5.984***	I(1)
In(EGC)2	-0.360	-6.425***	-0.747	-6.017***	I(1)
InREU	-0.741	-5.733***	2.916	-6.147***	I(1)
InNRR	-1.144	-6.425***	-0.747	-6.017***	I(1)
InGFN	-1.404	-7.433***	-1.697	-7.421***	I(1)
InAGRIC-VA	1.091	-4.442***	1.990	-6.654***	I(1)
ICT	0.359	-3.645***	-0.683	-3.445***	I(1)

Note: 1% denotes the level of significance

**Table 5** Synopsis of co-integration test

(Pedroni, 1999, 2004)					
Within Dimensions	Stats	Prob	Between dimensions	Stats	Prob
Panel v-Statistic	-1.692	0.974	Group rho-statistic	1.462	0.928
Panel rho-Statistic	0.342	0.754	Group PP-statistic	-7.773***	0.000
Panel PP-Statistic	-5.688***	0.000	Group ADF-statistic	-2.591***	0.000
Panel ADF-Statistic	-2.500***	0.000			
Weighted panel v-Statistics	-1.834	0.9667			
Weighted panel rho-Statistic	0.181	0.5718			
Weighted panel PP-Statistic	-5.832***	0.0000			
Weighted panel ADF-Statistic	-2.410***	0.000			
				(Westerlund, 2007)	
	(Kao, 1999)			Z-value	P-value
	t-Stats	Prob	$G_\tau$	-6.032***	0.000
ADF	-7.790***	0.000	$G_a$	1.254	0.904
			$P_\tau$	-5.491***	0.000
			$P_a$	0.430	0.726

Note: 1% denotes the level of significance

studies conducted by (Zakaria and Bibi 2019) in South Asian economies (Nathaniel et al. 2021) for G7 (Muhammad Awais Baloch et al. 2021), for BRICS (Kongbuamai et al. 2020) for ASEAN economies, and (Yang et al. 2021) for the Gulf Cooperation Council economies. However, studies conducted by (Destek et al. 2018; Usman et al.

2020) did not establish the presence of the EKC hypothesis in their findings.

Regarding the effect of biocapacity on ecological footprint, the research findings show a direct and positive connection between BIO and ecological footprint. The implication is that a 1% influence in the BIO will increase EFP

**Table 6** Synopsis of the outcome of CS-ARDL

Variables	Coefficient	Std. Error	Prob
<i>Short-run estimates</i>			
InBIO	0.291*	0.210	0.016
InEGC	0.284***	0.232	0.000
In(EGC)2	-0.197***	0.246	0.000
InREU	-0.329***	0.162	0.000
InNRR	0.573***	0.408	0.000
InGFN	-0.804*	0.010	0.028
InAGRIC-VA	0.090***	0.151	0.000
InICT	-0.026***	0.035	0.000
EMC (-1)	-0.75***	0.167	0.000
<i>Long-run estimates</i>			
InBIO	0.193	0.227	0.034
InEGC	0.298***	0.041	0.000
In(EGC)2	-0.228***	0.085	0.000
InREU	-0.242	0.063	0.000
InNRR	0.439	0.006	0.000
InGFN	-0.506**	0.005	0.013
InAGRIC-VA	0.151***	0.043	0.000
InICT	-0.024***	0.006	0.000
<i>EKC turning point</i>			
Countries	Lower bound	Upper bound	Extreme point
South Asian Economies	413	10,538	8712
			Structure
			Inverted U-Shape

Note: 1% denotes the level of significance

in the SSE by 0.291%, with all other factors remaining constant. Thus, a BIO that exceeds the EFP situation leads to environmental degradation and vice versa. The current study outcome is consistent with (Yang and Khan 2022) for International Energy Agency economies, (Unal and Aktug 2022) for G7, (Shujah-ur-Rahman et al. 2019) for Central and Eastern European economies, and (Hassan et al. 2019) for Pakistan who found a positive association between BIO and EFP.

Concerning the impact of REU on ecological footprint, the study found that REU dissipates EFP in South Asian economies. More specifically, REU has an inverse interaction with EFP. Thus, if REU is enhanced by 1%, environmental pollution will be reduced by 0.329% in the SSE. Therefore, this study's results provide a clear reason for using renewable energy sources to promote the economic development of both emerging and emerging economies. Usman and Hammar (2021) suggested that both government and enterprises adopt policies that can utilize REU to help overcome the pressure from GHG emissions on the environment. Sharma et al. (2021) concluded that the increased use of REU has improved EFP in the SSE. Hence, this study emphasizes that SSE should minimize non-renewable energy sources and rely more on REU for their economic expansion to optimize environmental quality. The findings of this research back up these studies (Akinsola et al. 2022; Balsalobre-Lorente et al. 2019a, b; Caglar et al. 2022; Usman and Makhdom 2021). However, some research has found that intensifying renewable energy consumption will contribute to environmental degradation (Ben Jebli et al. 2015; Paramati et al. 2021).

The interaction between NRR and ecological footprint disclosed that NRR has a significant positive influence on EFP in South Asian economies. Accordingly, a 1% rise in NRR will increase EFP by 0.573%. The intuition behind this finding is that the South Asian economies still use obsolete technology and traditional energy sources to exploit their natural resources, contributing to environmental degradation in these regions (Chopra et al. 2022; Ibrahim and Ajide 2021). Further, the assumption that the use of NRR would explicitly enhance economic progression, which in turn decreases ecological integrity in these economies, is one possible explanation for these findings. The findings support the assertion that the availability of NRR leads to a lower level of resources, which impedes enterprises' diversification agendas and leads to wasteful resource consumption, which has implications for the sustainability of EFP (Caglar et al. 2022; Erdogan et al. 2021; Xu et al. 2022). In contrast, Xiaoman et al. (2021) discovered that NRR has an inverse relationship with EFP in the Middle East and North America (MENA). According to their findings, the governments of the MENA countries use a safe mechanism to extract natural minerals by using green technology, which reduces EFP.

Pertaining to the influence of GFN on EFP, the study unearthed that GFN negatively affects EFP. The empirical results reveal that a 1% upsurge in GFN can suppress EFP by 0.804% in the SSE. Financial investment in green production implies that businesses will use less polluting technology in their manufacturing processes. Zakari and Khan (2022) noted environmental sustainability could be enhanced through green financial development. GFN impacts consumers and businesses, stimulating them to buy green and low-carbon products that are less harmful to the environment (Chen and Chen 2021). The empirical results corroborate with previous studies, which show that GFN is an efficient and productive financial approach to enhancing the sustainability of the environment (Nawaz et al. 2021; Shen et al. 2021).

Furthermore, the interaction between AGRIC-VA and EFP revealed that in the SSE, AGRIC-VA has a significantly positive relationship interplay with EFP. Thus, the inference is that a 1% rise in AGRIC-VA can result in the will EFP escalating by 0.090%. This outcome indicates that agriculture activities contribute to the high level of EFP in the SSE. AGRIC-VA is an innovative perspective in agriculture production that may increase farmer profitability and job stability in the agro-based business but may jeopardize biodiversity (Usman and Makhdom 2021). The intuition for the positive interaction between AGRIC-VA and EFP is that most farmers in the SSE do not apply more advanced technology and renewable energy sources in their agricultural activities, which contributes to the high level of EFP in these

**Table 7** Robustness tests

Variables	Coefficient	Std. Error	Prob
<i>AMG estimates</i>			
InBIO	0.639*	0.271	0.027
InEGC	0.366***	0.283	0.000
In(EGC)2	-0.277***	0.143	0.000
InREU	-0.325***	0.072	0.000
InNRR	0.168***	0.013	0.000
InGFN	0.007*	0.011	0.055
InAGRIC-VA	0.216***	0.021	0.000
InICT	-0.038**	0.012	0.002
<i>CC-MG estimates</i>			
InBIO	0.372***	0.230	0.000
InEGC	0.356***	0.068	0.000
In(EGC)2	-0.228***	0.085	0.000
InREU	-0.253***	0.112	0.000
InNRR	-0.552***	0.918	0.000
InGFN	-0.039*	0.008	0.015
InAGRIC-VA	0.404***	0.050	0.000
InICT	-0.805***	0.016	0.000

Note: 1% denotes the level of significance



regions. Salari et al. (2021) indicated that agricultural activities are a major cause of GHG emission, the consumption of about 70% of freshwater and biodiversity. The findings of this study support these studies (Pata 2021; Qiao et al. 2019; Udemba 2020; Usman and Makhdum 2021). However, the present research result contrasts with (Jebli and Youssef 2017; Ridzuan et al. 2020), who reported that AGRIC-VA enhances environmental sustainability.

Regarding the influence of ICT on EFP, these results indicated that ICT has a significant adverse impact on EFP. More precisely, a 1% increase in ICT will dissipate EFP by 0.026% in the SSE. The interpretation behind this result can be based on the presumption that ICT reduces environmental pollution by enhancing energy efficiency and savings. Further,

ICT encourages enterprises to adopt modern technologies in their business process, which helps reduce emissions (Huang et al. 2022). This study aligns with prevalent environmental scientists who argue that ICT effectively promotes environmental sustainability. Nevertheless, some scholars provide empirical results that indicate that the ICT process, production, and related activities require more energy, which increases environmental deterioration (Caglar et al. 2022; Godil et al. 2020; Haldar and Sethi 2022; Silva et al. 2022).

Finally, the error correction coefficient value (EM-1) is statically significant and inversely related to EFP. The implication is that, after being impacted by 75% in the short run, SSE economies should provide an efficient solution to environmental degradation in the coming years. The AMG and

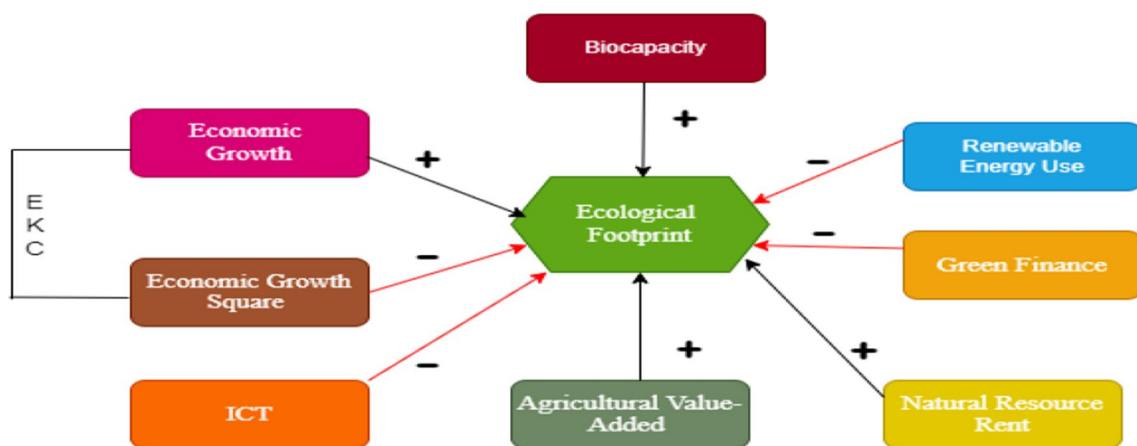


Fig. 9 Graphical presentation of empirical results of the study

Table 8 Findings of pairwise Dumitrescu and Hurlin panel causality test

Null Hypothesis	W-stat	Z-bar-Stat	Prob	Conclusion
InBIO ⇄ InEFP	6.117***	6.794	0.000	BIO ↔ EFP
InEFP ⇄ InBIO	3.586***	3.372	0.000	
InEGC ⇄ InEFP	7.023***	8.018	0.000	EGC → EFP
InEFP ⇄ InEGC	1.618	0.712	0.475	
InEGC2 ⇄ EFP	7.005***	7.994	0.000	EGC2 → EFP
InEFP ⇄ In EGC2	1.617	0.711	0.477	
InREU ⇄ EFP	4.778***	4.983	0.000	REU → EFP
InEFP ⇄ REU	1.997	1.224	0.220	
InNRR ⇄ InEFP	7.029***	5.279	0.000	NRR ↔ EFP
InEFP ⇄ InNRR	5.779***	6.337***	0.000	
InGFN ⇄ InEFP	6.620***	7.473	0.000	GFN → EFP
InEFP ⇄ InGFN	2.538	1.955	0.050	
InAGRIC-VA ⇄ InEFP	5.392***	5.814	0.000	AGRIC-VA → EFP
InEFP ⇄ InAGRIC-VA	1.651	0.757	0.448	
InICT ⇄ InEFP	7.458***	8.606***	0.0000	ICT ↔ EFP
InEFP ⇄ InICT	4.065***	4.020	0.001	

Note: 1% denotes the level of significance. The symbols ⇄ (does not homogeneously cause), ↔ (bidirectional), and → (Unidirectional)

CC-MG approaches analyzed the research's robustness test. The AMG and CC-MG estimators are consistent with the CS-ARDL outcome, as shown in Table 7. Furthermore, the signs for all selected series are identical, indicating that the CS-ARDL results were reliable. Figure 9 depicts the empirical findings from this study in a graphical format.

### Dumitrescu and Hurlin causality test

Only short- and long-term estimates are provided by the CS-ADRL method. As a result, these approaches fail to show a causal relationship between series in panel data. The causality relationship must be investigated to recommend integrated and coordinated initiatives to stakeholders and policy experts. The research used a novel strategy advocated by Dumitrescu and Hurlin (2012) to analyze the causality interactions among the series. The  $W$ -bar and  $Z$ -bar statistics are calculated using this method. Table 8 displays the results of the D-H non-causality test. The findings demonstrated a one-way causality relationship between economic growth and EGC2, renewable energy use, green finance, and agricultural value-added to EFP. These findings suggest that policies promoting economic growth and square of economic growth, renewable energy use, green finance, and agricultural value reduce EFP in the sample economies. Furthermore, the D-H causality results show that natural resource rent, biocapacity, ICT, and EFP have a bidirectional relationship. This means that any policy focused on NRR, URB, and URB in common terms can reduce EFP in South Asian economies at the same time.

## Conclusion and policy recommendations

### Conclusion

This paper examines the interplay of economic growth, biocapacity, renewable energy use, natural resource rent, agricultural value-added, green finance, ICT, and ecological footprint in South Asian economies. The research employed data from 1990 to 2017 and investigated the association between EGC and ecological footprint within the EKC theory. Initially, this research analyzed the CSD test, unit root, and co-integration interaction among the series. Finally, this research used an advanced strategy proposed by Dumitrescu and Hurlin (2012) to examine the causality relationship between the series.

This research draws the following conclusion; (1) this research found an inverted existence of the EKC hypothesis in the South Asian countries. (2) this study outcome concluded that agriculture value-added, natural resource rent and biocapacity cause an upsurge in EFP (3) further,

renewable energy use, green finance, and ICT dissipate ecological footprint. (4) the outcome from the D-H causality test revealed a one-way causality association flowing from renewable energy use, economic growth, green finance, and agricultural value-added to EFP. (5) lastly, causality outcomes indicate a two-way interaction between natural resource rent, biocapacity, ICT, and EFP.

### Core policy framework

Based on the empirical findings of this investigation, this research posits the policy framework outlined below to aid in the improvement in environmental quality and sustainability. First, the EKC hypothesis in these regions requires these economies to focus on domestic consumption, notably in areas that heavily depend on conventional energy sources to manufacture goods. As a practical matter, environmental protection laws, standards, and initiatives should be used to control industrial processes that produce relatively high carbon emissions (Cai et al. 2022; A. Sampene et al. 2021). Secondly, one of the critical outcomes of this research is that biocapacity increases the level of EFP in the SSE. Therefore, stakeholders and government should undertake policy initiatives to improve biocapacity without affecting EFP. Environmental disruptions will be mitigated, and resources will revitalize as monitoring, and sustainable alternatives are interconnected into production and supply, reducing the predisposition for biodiversity loss.

Thirdly, considering the inverse interplay between REU and EFP in the SSE, this research recommends that stakeholders adopt a system that can check enterprises that use renewable energy sources for production. Thus, the proposed approach can help establish a clear target for companies adopting REU. In addition, government budgets in these regions should allocate enough funds for research and development of REU, for instance, biofuel, biomass, hydropower and wind. Government and policymakers can create public awareness about the importance of using more renewable energy sources. Fourth, the present research envisioned that policymakers should establish appropriate strategies for achieving consistent natural resource utilization to counteract the contribution influence of natural resource rent on EFP. It is also imperative to use innovative technologies and techniques to harness these countries' natural resources to reduce pollution and environmental degradation.

Fifth, regarding the adverse impact of green finance on environmental pollution, more awareness of the concept of GFN among various stakeholder groups and policy experts is required. Sixth, based on the positive interaction



between AGRIC-VA and EFP, this research deduces that the dependence on agriculture for economic development seriously impacts environmental pollution. Hence, stakeholders should educate farmers on using advanced technology and agriculture mechanization for agriculture activities (Brenya et al. 2022; Gangwar et al. 2022; Sampene et al. 2022). Lastly, this research outcome revealed that ICT advancement enhances environmental sustainability. Therefore, this research urges the South Asian economies to keep updating and revamping their ICT framework to recoup the double benefits of higher industrial productivity and mitigate EFP. ICT development is generally connected to adopting cleaner, modern, renewable, and sustainable practices that improve environmental sustainability.

### Limitation and future research

This study has some limitations, which allows us to conduct more research in the future to address these issues. First, this research model did not incorporate other essential variables affecting EFP, such as good governance, regulatory quality, and human capital. Integrating these variables and using other environmental theories like the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model will allow the researchers to expand their research in the future. Furthermore, interaction variables such as globalization could be used to examine the influence of these factors on pollution in other jurisdictions.

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**Data availability** WID: <https://databank.worldbank.org/source/world-development-indicators#>

OECD: <https://data.oecd.org/envpolicy/patents-on-environment-technologies.htm>

Global Footprint Network: <https://www.footprintnetwork.org/>.

### Declarations

**Conflict of interests** No potential conflict of interest was reported by the author.

**Ethical approval** This article does not contain any studies with human participants performed by any of the authors.

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