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The effect of public–private partnership investment, financial development, and renewable energy consumption on the ecological footprint in South Asia and the Pacific region

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The improvement of environmental quality has become a major challenge for all countries. Against the strategic background of environmental protection, this study investigated the role of public–private partnership investment (PPPI) in energy and transport, financial development, and renewable energy on ecological footprint (EF) in South Asia and the Pacific region, utilizing the autoregressive distributive lag (ARDL) model spanning the time 1990–2017. The outcomes of the ARDL show that PPPI in energy and transport has a significantly positive effect on the EF in the full sample and Pacific region in the long run. Financial development has a positive impact on the EF in South Asia and the Pacific region in the long term. Renewable energy causes a significant and negative impact on the EF in the full sample in both time periods, and only in the short run in South Asia. As for the panel granger causalities test, PPPI in energy and transport and renewable energy has a negative causal relationship with the EF. The results also reveal that there is a unidirectional negative and positive causality from financial development to the EF in the long term in South Asia and the Pacific region, respectively. On the basis of the analysis, corresponding recommendations are proposed.

KEYWORDS

public–private partnership investment, financial development, renewable energy consumption, ecological footprint, ARDL model

1 Introduction

The process of industrialization and economic growth has exerted significant negative externality on ecological quality for decades. Environmental degradation is progressively demonstrating to be the prime challenge faced by nations across the globe. The excessive utilization of traditional fossil fuels such as coal, oil, and natural gas, as well as various social activities, along with the increase in consumerism, are discerned as the drivers of emitting a high quantity of CO_2 into the environment (Kirikkaleli and Adebayo, 2021a; Shahzad et al., 2021). Policymakers, conservationists, researchers, and international organizations focused on these issues, while issued conference documents such as the United Nations Framework Convention on Climate Change, Marrakesh Accords, the Paris Agreement, the Kyoto Protocol and its Doha Amendment, and the UN Sustainable Development Goals have discussed and highlighted such problems, for which a large number of countries are gradually turning out to be laggards in achieving a socio-ecological balance. Despite the frequent occurrence of natural disasters and the precarious environment, the crusade against natural resources has never stopped, which stems from the pursuit of economic development and improvement of living standards (Alshehrya and Belloumi, 2017; Nathaniel and Bekun, 2020). However, owing to increasing greenhouse gas emissions, policy analysts have begun to shift their emphasis toward the use of renewable energy consumption in terms of solar PV, hydropower, wind, tidal and geothermal, and biomass to attain the sustainable development objective (Roy and Singh, 2017; Charfeddine and Kahia, 2019; Yuping et al., 2021). In addition, the path to carbon emission reduction must lead to enhancing the role of technology innovation in mitigating the deterioration of environmental quality (Georgatzi et al., 2020; Wen et al., 2020). Technological reforms are beneficial to improving energy efficiency and increasing the flexibility of the economic system *via* developing high-efficiency technologies that lower the intensity of carbon emissions (Khan H. et al., 2020; Wei et al., 2020). Renewable energy has been confirmed to be attributed to environmental quality, but its construction requires a lot of capital inflows, and relying on public investment alone is far from meeting the real needs. In this context, public–private partnership investment (PPPI) is gradually acquiring eminence in sustainable development, leading to numerous individual capital investments in low-carbon projects in the form of decentralized infrastructure installation and energy production, which bring about the rise of the green economy (Newcomb et al., 2013; Adebayo et al., 2021a).

As regards the research in ecological quality, numerous research studies have confirmed the predictions of the Kuznets curve in many different regions (Talbi, 2017; Zhang and Zhang, 2018) and investigated the factors that may influence environment depletes, for instance, economic growth (Alshehrya and Belloumi, 2017; Zhang et al., 2021), human activities (IPCC, 2018; Odugbesan and Adebayo, 2020), urbanization (Xu and Lin, 2015; Mahmood et al., 2020), financial development (Shahbaz et al., 2017; Kirikkaleli and Adebayo, 2021a; Adebayo et al., 2021b), technology innovation (Verdolini et al., 2018; Ganda, 2019; Adebayo et al., 2021a), energy consumption (Adebayo and Akinsola, 2021; Murshed et al., 2021), and population factors (Wu et al., 2019; Musah et al., 2021). More specifically, economic development is always accompanied by a large amount of energy consumption, especially nonrenewable energy; therefore, economic performance and energy consumption reinforce each other incessantly, resulting in serious and harmful environmental consequences (Xu and Lin, 2015). Moreover, population growth and urbanization, especially in developing countries, are understood to be the significant factor triggering environmental deterioration (Chen et al., 2022). Renewable energy sources show potential in restraining environmental degradation, but their usage is currently underrepresented compared to nonrenewable energy (Shafiei and Salim, 2014; Aslan et al., 2021), and the effect of renewable energy on ecological quality has not reached the ideal state. Meanwhile, innovations in energy-saving technologies and increased financing for environmentally friendly enterprises will contribute to ecological improvement. However, scholars' research on the impact of financial development on environmental quality has not yet reached a definitive conclusion, and empirical results vary according to sample groups, data intervals, proxy variables, and other heterogeneity factors (Salahuddin et al., 2015; Charfeddine and Kahia, 2019; Fávero et al., 2022).

At the same time, a flood of literature reports are interested in substituting carbon emissions with the ecological footprint (EF) or biocapacity as a proxy for environmental quality, along with several economic indicators to consider economic–ecological sustainability (Ahmed et al., 2021; Khan and Hou, 2021; Rout et al., 2022). The EF is also known as the appropriate carrying capacity, referring to a geographical region which can sustain human survival, accommodate human waste, and be biologically productive. Obviously, it clearly reflects the impact of human activities on the ecology and the limits of human development in a specific area as well (Stöglehner, 2003). In addition, the advantage of the EF over CO_2 is that it takes into account the influence of the anthropogenic nature on ecological maintenance (Nathaniel et al., 2019). Some studies have identified that nonrenewable energy consumption is the driving indicator of ecological deterioration (Nathaniel et al., 2019; Khan and Hou, 2021), whereas technological innovation and financial development may be expected to have positive spillovers on the EF in the long run (Naqvi et al., 2021; Rout et al., 2022).

At this stage, the research on the influencing factors of climate change has been relatively sufficient, but the destruction to the ecosystems is still deepening, indicating that there are problems in the practice of implementing low-carbon

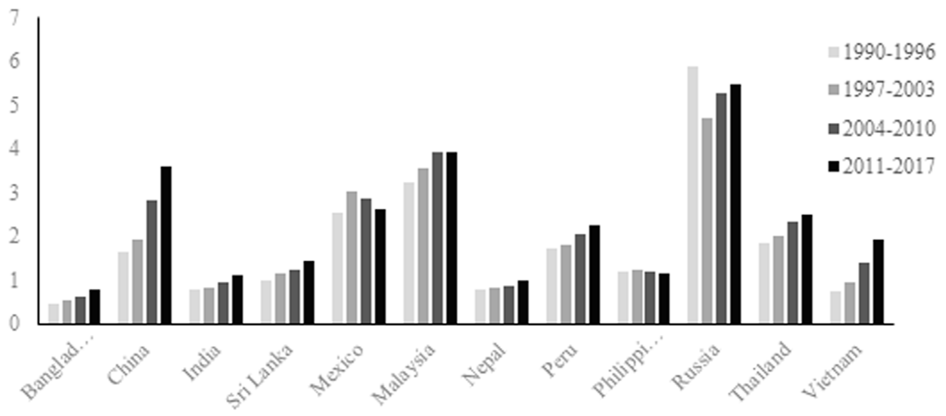

FIGURE 1
Average value of the ecological footprint in different time periods.

intensity. In this regard, it is believed that there exist two routes to achieve low-carbon goals: one is to promote the utilization of renewable energy and gradually substitute fossil fuels (Dogan et al., 2019; Qiao et al., 2019; Sharma et al., 2021) and the other is to develop high-efficiency technologies to increase the marginal output per unit of energy, thus reducing pollutant emissions (Dinda, 2018; Yao et al., 2021). However, both the major solution tools require considerable support from the government (Aslan et al., 2021). Against this background, PPPI has become a prevailing method to reduce the burden on the government in the form of constructing infrastructure, R&D, and green promotion, enabling theoretical solutions to be practically implemented in the society (Forrer et al., 2010; Siemiatycki, 2015). At present, the research on PPPI is mainly divided into transportation and energy aspects. High fossil fuel consumption in transport in developing nations makes economic development patterns unsustainable, and PPPI in transport should concentrate on increasing the use of renewable energy in the industrial sector (Anwar et al., 2021). Likewise, PPPI in energy serves as a catalyst for the emanation of CO_2 in the long run, which also conveys that the share of renewable energy utilization is relatively low (Kirikkaleli and Adebayo, 2021b). However, there is a lack of research on the impact of PPPI under the framework of ecological economy; thereby, further research is needed.

In this study, we attempt to examine the nexus among PPPI, financial development, renewable energy, and the EF in South Asia and the Pacific region, which consists of Nepal, Mexico, Peru, Russia, Bangladesh, China, India, Sri Lanka, Malaysia, Philippines, Thailand, and Vietnam. Economic growth is directly linked to energy consumption, and more environmental emanation can be observed in developing countries (Erdogan et al., 2020), where energy-intensive development is placing a huge burden on the environment (Zhang et al., 2019; Wang and Zhang, 2020). Hence, it is more urgent for these nations to solve ecological deterioration. With regard to policy formulation, it needs to consider finance and renewable energy consumption as the major determinants of ecological quality so that its environmental carrying capacity can be examined. Furthermore, in order to visually observe the changes in the ecological footprint of each country, the per capita EF is averaged every 7 years for the time period of 1990–2017, and four periods of values can be obtained. Figure 1 presents the averaged value of the per capita EF in different time periods of these countries. It can be seen that the per capita EF in most countries is gradually increasing, showing that their economic-oriented policies are very dangerous signals for environmental governance.

Meanwhile, Figure 2 presents the averaged value of the per capita EF in South Asia, the Pacific region, and the total samples. We can conclude that the overall trend of the per capita EF values of South Asian and Pacific countries is gradually increasing, and the ecological environment is still deteriorating. Therefore, this motivates us to investigate the impact of PPPI in transport and energy, renewable energy, and financial development on the ecological footprint, incorporating technology innovation and urbanization in South Asia and the Pacific region.

The study makes three main contributions. First, developing countries must solve thorny and urgent environmental problems and pursue stable economic development at the same time. The development of PPPI plays a key role in achieving the dual goals. As a consequence, we can provide them with suggestions for formulating environmental protection policies. Second, carbon emissions caused by the transportation sector and energy consumption are the two main sources of greenhouse gas emissions. To the best of our knowledge, there is no article available that combines PPPI in transport and energy, financial development, renewable energy, and ecological footprint in developing countries. Therefore, we attempt to fill the gap in

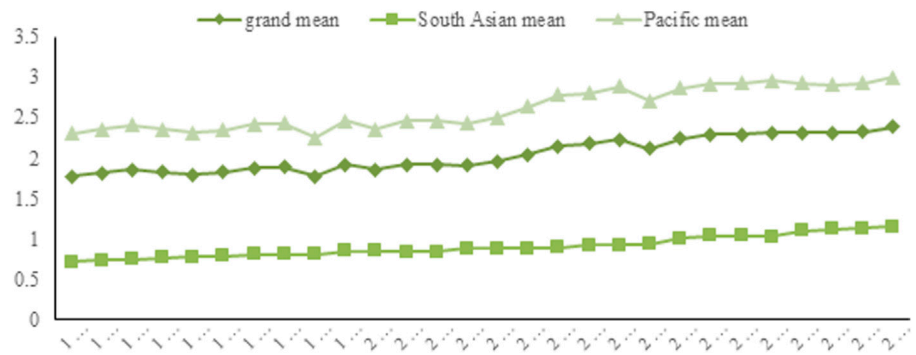

FIGURE 2
Average value of the ecological footprint in different regions.

the empirical literature by providing a comprehensive analysis of whether the joint investment of the government and the private sector can accelerate the sustainable development of the environment. Third, we applied the autoregressive distributed lag (ARDL) model to explore the long-term and short-term nexus among the variables, and the panel granger causality test was employed to check the causal relationship between the indicators.

The remaining sections of this paper are structured as follows. Section 2 covers the review of the existing literature. Section 3 covers the data and methodology adopted for the research. Section 4 presents the empirical results and discussions. Section 5 entails the conclusion and policy recommendations.

2 Literature review

This paper explored the connection between PPPI, financial development, renewable energy, and ecological footprint by taking into account the role of technological innovation and urbanization. Hence, it is reasonable for us to split the available literature review into three sections: the association between PPPI and EF, financial development and EF, and renewable energy and EF.

2.1 Public–private partnership investment and ecological footprint

In developing countries, the environmental impact of PPPI in terms of infrastructure and energy is very critical, but the current research on the relationship between PPPI and economic quality is very limited. For Pakistan, Chunling et al. (2021) looked into the nexus among PPPI in energy, technology innovation, and EF utilizing the ARDL model for the time 1992–2018 . They noted that the two aforementioned variables are positively related with the EF. Likewise, Akinsola et al. (2022) demonstrated that PPPI in energy is unfavorable for environmental quality in the case of Brazil. In addition, several studies use carbon emissions as a proxy variable for environment discharge. According to Khan Z. et al. (2020), PPPI has a positive impact on consumption-based carbon emissions, while technological innovation triggers environmental improvement in China. This is similar to the results obtained by Adebayo et al. (2021a) for East Asia and the Pacific region and Kirikkaleli and Adebayo (2021b) for India. However, a study by Anwar et al. (2021) analyzed the asymmetric effect of PPPI in the transport sector and energy consumption on transport-induced CO_2 emissions, integrating urbanization into the carbon equation in the case of China for the period 1991Q1–2018Q4. Their results showed that PPPI in transport is negatively related to carbon emissions, and policymakers need to decrease the subsidies on nonrenewable energy. A study by Van Song et al. (2021) explored the role of PPPI in carbon emissions and PM2.5 during 1990–2015 in the region of the USA. Their empirical results revealed that PPPI contributes toward environmental abatement. As a result of the limited amount of research on the given topic, we included studies examining the role of public investment or private sector investment on environmental sustainability. In the case of eight Asian economies, Lin and Omoju (2017) documented that private sector investment in transport exerts positive externality on carbon emission reduction, while economic growth and urbanization are devoted to traffic-induced carbon emissions, on the basis of scrutinizing the nexus between private sector investment in transport CO_2 emissions, economic growth, and urbanization. As investigated by Alvarez-Herranz et al. (2017), public investment in energy R&D and renewable energy are the core contributors of enhancing environmental sustainability in the OECD region, signaling that these factors are favorable for achieving green development. Kassouri (2021) employed water, land, and ecological footprints as metrics to characterize human-induced pressures on the biodiversity, and he pointed out that urbanization contributes to the expansion of human-induced pressures on water and built-up landscape.

2.2 Financial development and ecological footprint

Financial development is not only directly related to the performance of the macro-economy but also penetrates the clothing, food, housing, transportation, and production activities of residents to affect the carrying capacity of the environment. Destek and Sarkodie (2019) scrutinized the role of financial development on the EF for 11 industrialized nations covering the period 1977–2013 and confirmed that the impact of financial development on the environmental quality is not consistent across countries. Likewise, Pata and Yilanci (2020) reported that financial development plays a different role in the EF of G7 economies. For the case of 155 countries, Naqvi et al. (2021) reported that financial development has a substantially negative and positive influence on the EF in high- and low-income nations. Furthermore, Zeraibi et al. (2021) demonstrated that the development of finance and economics contributes to the EF in ASEAN-5 nations during the period of 1985–2016. Chen et al. (2019) discovered a feedback relationship between financial development and EF in 16 CEE countries from 1991–2014. Similarly, Khan et al. (2019) obtained consistent results while examining a finance-driven emissions hypothesis in Belt and Road initiative regions. Hafeez et al. (2018) suggested that BRI economies should improve financial legislation to control financial sector activities and allocate more funds to clean energy projects. In addition, the government can provide preferential policies to environmental protection enterprises and tax polluting industries to give them an incentive to change production methods (Baloch et al., 2019). Some scholars have also concluded that the development of the financial sector will worsen the environmental quality by increasing the ecological footprint in different regions. Examples are as follows: Nathaniel et al. (2019) for South Africa, Ahmed et al. (2021) for Japan, Zia et al. (2021) for China, Khan et al. (2021) for Malaysia, Kihombo et al. (2021) for West Asia and the Middle East nations, Godil et al. (2020) for Turkey, Omoke et al. (2020) for Nigeria, Nathaniel (2021) for N11 countries, and Yang et al. (2021) for BICS nations. However, Usman et al. (2021) showed a significantly negative effect of financial development on the EF in 15 highest-emitting countries in the world.

2.3 Renewable energy and ecological footprint

Previous research has concentrated on the impact of renewable energy on carbon emissions (Al-Mulali et al., 2015; Roy and Singh, 2017; Roy et al., 2018; Charfeddine and Kahia, 2019; Qiao et al., 2019; Khan H. et al., 2020; Wang et al., 2020; Adebayo and Akinsola, 2021; Yuping et al., 2021). Given the comprehensive nature of EF indicators, there is a growing emphasis on the influence of renewable energy on the EF, and most studies have revealed that the widespread use of renewable energy can significantly reduce the ecological footprint (Charfeddine, 2017; Sharma et al., 2021). For instance, Naqvi et al. (2020) explored the link between renewable energy, real income, trade openness, and EF in a panel of 152 countries from 1990 to 2017. Findings showed that openness and renewable energy usage have considerable impact on EF reduction in high- and upper-income nations, thereby promoting environmental sustainability. Similarly, Usman and Hammar (2021) found that renewable energy effectively reduces the EF by 0.4274% in APEC countries. In another study, Usman and Makhdum (2021) reported that for every 1% increase in renewable energy, the EF will decrease by 0.2248%. In a recent study, Vo (2022) showed the existence of bidirectional causality between financial development, renewable energy usage, and economic growth; hence, increasing the proportion of renewable energy utilization could help nations achieve the dual goals of economic development and ecological sustainability. In addition, Dogan et al. (2019) documented that fossil fuel energy and urbanization have caused great pressure on the environment, and the positive validity of renewable energy consumption varies across countries in the MINT group. As investigated by Caglar et al. (2021), alternative energy accelerates the improvement of the environmental quality in the top 10 pollutant emission nations. This is similar to the findings obtained by Usman et al. (2020) that renewable energy would ease environmental damage in the USA, Sharma et al. (2021) for eight developing countries in Asia, Destek and Sinha (2020) for OECD regions, and Rout et al. (2022) for the BRICS countries. However, Nathaniel et al. (2020) discovered that renewable energy has no obvious effect on the economic improvement in the MENA region. To address the environmental issues, policymakers should diversify the use of renewable energy and gradually decarbonize economic activity, with the aim of effectively advancing the implementation of environmental policies (Baz et al., 2020). Moreover, Cruz and Katz-Gerro (2016) highlighted the importance of adopting energy efficient technology. Alola et al. (2019) proposed that green economic policies should focus more on structural measures, pay attention to women's employment and reproductive behavior, and optimize biocapacity from a population perspective. Sahoo and Sethi (2021) examined the linkage between energy consumption, human capital, and EF in developing countries and claimed that the quality of education and the amount of funding available in the renewable energy sector are the keys to reducing carbon intensity. Kassouri et al. (2022) investigated the determinants of renewable energy in 14 European countries from 1990 to 2016, which provides a good reference for this paper to study the potential transmission mechanism of the ecological footprint.

To summarize, we have reviewed the literature on the link among PPPI, renewable energy, financial development, and ecological footprint in the current paper, whereas the outcomes are inconsistent and the reason behind the scenario lies in the difference in the inherent structure of the contexts, data, and methodologies. Next, we will analyze from the empirical aspect.

3 Methodology

3.1 Data, variables, and descriptive statistics

Following Nathaniel et al. (2019), Zeraibi et al. (2021), Chunling et al. (2021), Anwar et al. (2021), and Akinsola et al. (2022), our study takes account of the panel data of ecological footprint, public–private partnership investment in energy and transportation, renewable energy consumption, financial development, urbanization, technology innovation, and population density from 1990 to 2017 for 12 South Asian and Pacific countries. The assortment of sample size was based on data availability. The empirical model can be specified as follows:

$$\ln EF_{it} = \alpha_0 + \alpha_1 lnENI_{it} + \alpha_2 lnTRI_{it} + \alpha_3 \ln REC_{it} + \alpha_4 \ln FD_{it} + \alpha_5 \ln URB_{it} + \alpha_6 \ln PAT_{it} + \alpha_7 \ln POD_{it} + \varphi_{it}, \quad (1)$$

where all of the indicators are transformed into their logarithms, $ln\,EF$ is a substitute for ecological footprint, and $lnENI$ and $lnTRI$ are used for PPPI in energy (1,990 US$) and PPPI in transport (1,990 US$), respectively. $lnREC$ is the renewable energy consumption (% of total final energy consumption), and $lnFD$ is the financial development, which is measured by financial institutions and financial markets. In previous studies, applying the ratio of private credit to the GDP or stock market capitalization to the GDP to represent financial development did not consider the multidimensional characteristics of finance (Svirydzenka, 2016). Urbanization is indicated by $lnURB$, which uses the urban population as % of the total population, and $lnPAT$ is used for technological innovation, which is measured by the number of patent applications by residents and nonresidents. $lnPOD$ refers to the population density (people per sq. km of land area). The subscript i shows the countries (1, 2, 3 ...12), t represents the time period (1990, 1991, 1992 ... 2017), α_0 indicates the intercept parameter, α_k (k = 1, 2, 3 ... 7) denotes the parameters for the elasticities of the EF, and φ_{it} is the error term. Data on PPPI in energy and transport, urbanization, technological innovation, and population density were collected from the World Bank, data on the ecological footprint were derived from the Global Footprint Network, data on renewable energy consumption were gathered from the OECD database, and data on financial development were extracted from the IMF database.

Correspondingly, Table 1 presents the measurement and data source of the indicators in the paper. Table 2 shows the descriptive statistics with relevant variables. It can be concluded that the selected variables have no outliers, and the multicollinearity test showed that the maximum variance inflation factor (VIF) value was 4.71, and the mean of the VIF values was 4.09, which were all less than 10, demonstrating that there was no multicollinearity between variables.

3.2 Econometric methods

First, we explored the unit root properties of the variables with the LLC test, which was proposed by Levin et al. (2002), to make sure that the sequence is stationary and the empirical validity of the series. In order to examine whether $\{y_{it}\}$ contains the unit root, we conducted the following panel autoregressive model:

$$\Delta y_{it} = \delta_i y_{i,t-1} + z_{it}^{'}\gamma_i + \varepsilon_{it}, \quad (2)$$

where y refers to each variable, subscript i (1, 2, 3 ... 8) is the cross-section unit, and t (1990, 1991, 1992 ... 2017) is the time period. $z_{it}^{'}\gamma_i$ represents individual fixed effects, and ε_{it} indicates the stationary disturbance term. Since the disturbance term of Eq. 1 may have autocorrelation, a higher-order difference lag term is introduced on the basis of Eq. 1, and the model is transformed into

$$\Delta y_{it} = \delta y_{i,t-1} + z_{it}^{'}\gamma_i + \sum_{j=1}^{p_i} \theta_{ij}\Delta y_{i,t-j} + \varepsilon_{it}, \quad (3)$$

where δ is the common autoregressive coefficient, and the lag order p_i of different variables is unknown. At this time, $\{\varepsilon_{it}\}$ becomes a stable ARMA process, and ε_{it} of different indicators is independent of each other. The LLC test obtains the residual $\widehat{e_{it}}$ from Eq. 2 and standardizes it to obtain the estimated coefficient $\hat{\delta}$ and the corresponding t statistic t_{δ}.

Second, this study adopted the Pedroni (1999) cointegration test to determine whether there is a long-term relationship between the variables. Only when there exists a cointegrating nexus of the variables can we effectively estimate the long-term coefficient and error correction item, and then the short-term coefficient can be estimated.

Third, according to the results of the Hausman test, we choose the pooled mean group (PMG) method to estimate the panel autoregressive distributed lag (ARDL) model, which was proposed by Pesaran et al. (1999). The advantage of the PMG is that it can weaken variable endogenous effects on the estimation coefficient and allows the intercepts, short-term coefficients, and random disturbance items between different groups, but the long-term coefficient between different groups should be consistent. Then, the modeling

TABLE 1 Description of indicators.

Indicators	Symbol	Measure	Source
Ecological footprint	LnEF	Global hectares per capita	GFN
PPPI in energy	LnENI	Public–private partnership investment in energy (1990 US$)	WDI
PPPI in transport	LnTRI	Public–private partnership investment in transport (1990 US$)	WDI
Renewable energy consumption	LnREC	Renewable energy consumption to the total final energy consumption (%)	OECD
Financial development	LnFD	Financial development index consists of financial institutions and financial markets	IMF
Urbanization	LnURB	Urban population to the total population (%)	WDI
Technological innovation	LnPAT	Number of patent applications by residents and nonresidents	WDI
Population density	LnPOD	People per sq. km of land area (%)	WDI

TABLE 2 Descriptive statistics.

Variables	Observations	Mean	St. dev	Maximum	Minimum
lnEF	336	0.504	0.648	1.922	−0.812
lnENI	336	16.77	3.955	22.72	4.253
lnTRI	336	16.57	4.332	22.26	5.389
lnREC	336	3.220	1.010	4.555	0.671
lnFD	336	−1.165	0.476	−0.302	−2.554
lnURB	336	3.638	0.561	4.380	2.181
lnPAT	336	7.787	2.542	14.14	1.099
lnPOD	336	4.846	1.260	7.112	2.165

conditions are fulfilled after using the panel unit root and cointegration test, and we applied ARDL modeling to explore the short-run and long-run causalities of the variables. Following Khan et al. (2019) and Wang (2021), the model can be stated as follows:

$$\begin{aligned}\Delta EF_{it} = \alpha_i^0 &+ \sum_{f=1}^{l-1}\beta_{ij}^o \Delta EF_{i,t-f} + \sum_{j=1}^{m-1}\rho_{ij}^o \Delta ENI_{i,t-j} \\ &+ \sum_{l=1}^{n-1}\phi_{il}^o \Delta TRI_{i,t-l} + \sum_{r=1}^{p-1}\gamma_{ir}^o \Delta REC_{i,t-r} \\ &+ \sum_{u=1}^{q-1}\mu_{iu}^o \Delta FD_{i,t-u} + \sum_{v=1}^{r-1}\tau_{iv}^o \Delta URB_{i,t-v} \\ &+ \sum_{x=1}^{s-1}\varsigma_{ix}^o \Delta PAT_{i,t-x} + \sum_{y=1}^{w-1}\iota_{iy}^o \Delta POD_{i,t-y} + \eta_1 EF_{i,t-1} \\ &+ \eta_2 ENI_{i,t-1} + \eta_3 TRI_{i,t-1} + \eta_4 REC_{i,t-1} + \eta_5 FD_{i,t-1} \\ &+ \eta_6 URB_{i,t-1} + \eta_7 PAT_{i,t-1} + \eta_8 POD_{i,t-1} + \varepsilon_{i,t}.\end{aligned} \tag{4}$$

The equation for the long-term estimate is as follows:

$$\begin{aligned}EF_{it} = \mu_i &+ \sum_{f=1}^{l-1}\lambda_{1j} EF_{i,t-f} + \sum_{j=0}^{m-1}\lambda_{2j} ENI_{i,t-j} + \sum_{l=0}^{n-1}\lambda_{3j} TRI_{i,t-l} \\ &+ \sum_{r=0}^{p-1}\lambda_{4j} REC_{i,t-r} + \sum_{u=0}^{q-1}\lambda_{5j} FD_{i,t-u} + \sum_{v=0}^{r-1}\lambda_{6j} URB_{i,t-v} \\ &+ \sum_{x=0}^{s-1}\lambda_{7j} PAT_{i,t-x} + \sum_{y=0}^{w-1}\lambda_{8j} POD_{i,t-y} + \nu_{i,t}.\end{aligned} \tag{5}$$

Then, the ARDL model short-term estimation is also known as the error correction model, and the equation is as follows:

$$\begin{aligned}\Delta EF_{it} = \alpha_i^0 &+ \sum_{f=1}^{l-1}\beta_{ij}^o \Delta EF_{i,t-f} + \sum_{j=1}^{m-1}\rho_{ij}^o \Delta ENI_{i,t-j} \\ &+ \sum_{l=1}^{n-1}\phi_{il}^o \Delta TRI_{i,t-l} + \sum_{r=1}^{p-1}\gamma_{ir}^o \Delta REC_{i,t-r} \\ &+ \sum_{u=1}^{q-1}\mu_{iu}^o \Delta FD_{i,t-u} + \sum_{v=1}^{r-1}\tau_{iv}^o \Delta URB_{i,t-v} \\ &+ \sum_{x=1}^{s-1}\varsigma_{ix}^o \Delta PAT_{i,t-x} + \sum_{y=1}^{w-1}\iota_{iy}^o \Delta POD_{i,t-y} + aECT_{t-1} \\ &+ e_{i,t},\end{aligned} \tag{6}$$

where ECT_{t-1} refers to the error correction term. Also, at the last stage, we used the panel causality test to estimate the short-term and long-term causalities among the variables.

4 Empirical results and discussion

4.1 Panel unit root test

We performed the unit root test on the data for the full sample, South Asia, and the Pacific region, respectively, with the LLC test, and the results are given in Table 3. It can be seen that the variables selected in this study are nonstationary at levels, but they are all significant at 1% and 5% levels and integrated at the first-level difference I (1), demonstrating that the null hypothesis is rejected at the first-level difference. We can conclude that our data have first-order integration.

TABLE 3 Results of the LLC unit root test.

Variable	Full sample		South Asia		Pacific region	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
lnEF	−1.836** (0.033)	−10.230*** (0.000)	0.921 (0.178)	−6.888*** (0.000)	−2.815*** (0.002)	−7.871*** (0.000)
lnENI	−2.396*** (0.008)	−17.295*** (0.000)	−2.657*** (0.004)	−11.481*** (0.000)	−1.600* (0.055)	−13.437*** (0.000)
lnTRI	−2.803*** (0.003)	−13.174*** (0.000)	−2.968*** (0.002)	−8.456*** (0.000)	−1.715** (0.043)	−10.745*** (0.000)
lnREC	−2.326*** (0.010)	−7.709*** (0.000)	−3.240 (0.999)	−4.934*** (0.000)	−2.970*** (0.002)	−7.144*** (0.000)
lnFD	−1.635* (0.051)	−14.120*** (0.000)	−0.706 (0.240)	−8.131*** (0.000)	−1.788** (0.037)	−11.460*** (0.000)
lnURB	−5.055*** (0.000)	−2.272** (0.012)	−1.841** (0.033)	−2.829*** (0.002)	−4.356*** (0.000)	−2.117** (0.017)
lnPAT	−0.537 (0.296)	−12.530*** (0.000)	−0.048 (0.481)	−7.943*** (0.000)	−0.751 (0.226)	−10.054*** (0.000)
lnPOD	−0.409 (0.341)	−2.753*** (0.003)	0.680 (0.752)	−2.609*** (0.005)	−1.062 (0.144)	−2.141** (0.016)

Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively.

TABLE 4 Results of the Pedroni cointegration test.

Statistics	Full sample	South Asia	Pacific region
Modified Phillips–Perron	4.761*** (0.000)	2.634*** (0.004)	3.909*** (0.000)
Phillips–Perron	−8.526*** (0.009)	−2.187** (0.014)	−8.450*** (0.009)
Augmented Dickey–Fuller	−13.692*** (0.000)	−1.474* (0.070)	−10.122*** (0.000)

Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively. The data in parentheses are the *p*-values of the corresponding statistics.

4.2 Cointegration test

We employed the Pedroni cointegration test to examine the long-run relationship between the variables, and the results of the full sample, South Asia, and Pacific countries are given in Table 4. According to the values of three different statistics, the three groups of samples all reject the null hypothesis significantly, indicating that there is a long-term nexus among the variables.

4.3 Autoregressive distributive lag model

We conducted the long-run and short-run estimates of the full samples, South Asia, and Pacific nations with the ARDL model, and the findings are given in Table 5.

It can be found that ENI has a substantial positive effect on the EF, p-values against all of these effects are <0.01, and a 1% increase in PPPI in energy causes a long-run increase of 0.68% in the full sample and 1.79% in Pacific nations, whereas ENI exerts an insignificant and positive long-term influence in South Asia. In addition, short-run estimates show that ENI causes a negative but insignificant effect on the EF in all three groups. These results infer that PPPI in energy contributes to environmental degradation in the long-term in the Pacific region and the full sample, and the findings are in line with several previous studies, e.g., Khan Z. et al. (2020), Chunling et al. (2021), and Adebayo et al. (2021a). According to them, less PPPI funds flow to environmental protection and green projects and more to high-carbon emission categories in these developing countries.

Similarly, the TRI has a positive and considerable impact on the EF in the long run, and a 1% increase in the TRI increases the EF by about 0.52% and 1.87% in the full sample and Pacific region, respectively, while the TRI is not significant in the remaining region and time periods. The current findings suggest that PPPI in transport is devoted to ecological deterioration, indicating that the penetration rate of clean energy in the transportation sector is not high enough; thus, it shows a negative externality to the environment (Anwar et al., 2021).

The REC has a substantial and negative effect on the EF in both time periods in the full sample but not in the Pacific region. This means that a 1% increase in renewable energy consumption significantly decreases the EF by 39.3% and 39.6% in the long run and short run in the full sample, respectively. In South Asia, the REC only has a significant negative influence on the EF in the short run, which conveys that one unit increase in renewable energy usage decreases the EF by 87.8% in the short run. These findings are inconsistent with many past studies that suggested

TABLE 5 Empirical results of the ARDL model.

Variable	Full sample		South Asia		Pacific region	
	Long term	Short term	Long term	Short term	Long term	Short term
LnENI	0.00681***	−0.00370	0.00616	−0.00261	0.0179***	−0.00760
	(0.00142)	(0.00325)	(0.00622)	(0.00302)	(0.00657)	(0.00760)
LnTRI	0.00523***	0.00267	0.0369	0.0478	0.0187**	−0.00177
	(0.00186)	(0.00477)	(0.0401)	(0.0424)	(0.00806)	(0.00453)
LnREC	−0.393***	−0.396***	−0.329	−0.878***	0.00550	−0.130
	(0.0403)	(0.124)	(0.200)	(0.229)	(0.0395)	(0.107)
LnFD	−0.0120	0.0522*	0.341***	−0.102**	0.615***	−0.0941
	(0.0161)	(0.0295)	(0.119)	(0.0485)	(0.157)	(0.0584)
LnURB	0.463***	−12.70	−0.590*	4.757	0.518	−4.939
	(0.101)	(11.80)	(0.315)	(6.046)	(0.544)	(13.85)
LnPAT	0.0162**	0.0273*	−0.0107	0.00715	-0.117***	0.0658*
	(0.00782)	(0.0164)	(0.0335)	(0.0125)	(0.0383)	(0.0349)
LnPOD	−0.725***	−4.768	0.759	−2.070	-0.351	0.542
	(0.148)	(5.062)	(0.489)	(1.929)	(0.419)	(4.276)
LnECM	−0.469*** (0.109)		−0.375* (0.213)		−0.342*** (0.126)	
Observations	324		108		216	

Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively. The data in parentheses are standard errors.

that renewable energy plays a vital role in improving ecological quality, e.g., Charfeddine (2017), Jin and Kim (2018), and Rout et al. (2022). Furthermore, renewable energy works based on the energy structure. Nathaniel et al. (2020) demonstrated that renewable energy will not have a significant impact on the environmental quality if a country does not change its energy mix that relies on fossil fuels. Therefore, the government can strengthen the utilization of renewable energy to accelerate the reduction of carbon emissions.

FD has a considerable and positive impact on the EF in the long term in South Asia and Pacific nations, while it has a negative and insignificant influence in the full sample. Hence, it is found that one unit increase in financial development causes a significant long-run increase of 34.1% and 61.5% in South Asian and Pacific countries, respectively. For short term, FD exerts a substantial and positive effect on the full sample but a negative influence in South Asia, which means that a 1% increase in financial development causes a significant increase of 5.22% in the full sample but decreases the EF by 10.2% in South Asia. The results of the full sample are inconsistent with those of South Asia because the impact of financial development on the ecological footprint can be positive (Saud et al., 2020; Ahmed et al., 2021) or negative (Uddin et al., 2017; Ibrahiem, 2020) on the basis of theoretical analysis. The role of financial development on the ecological footprint also has multiple transmission channels. Financial development acts on consumers and heavily polluting enterprises through credit expansion, resulting in the expansion of the production scale and energy demand, which in turn has adverse effects on the environment. On the other hand, the development of the financial sector promotes the upgrading, deployment, and application of green technologies; stimulates the growth of environmental protection industries; and thereby enhances the improvement of the ecological environment.

The URB causes a significant and positive influence on the EF in the long run in the full sample, whereas it plays a negative role in South Asia. It can be seen that one unit increase in urbanization causes a considerable increase of 46.3% in the full sample and the EF decreases by 59.0% in South Asia in the long run. However, the URB exerts an insignificant impact on the remaining region and time periods. The results in South Asia are surprising since a number of previous research studies have shown that urbanization stimulates environmental degradation (Ahmad and Zhao, 2018; Baloch et al., 2019; Nathaniel et al., 2019). However, the positive spillover effect of urbanization on ecology may stem from the improvement in the urban infrastructure construction, management, and services.

The PAT has shown a substantial long-term positive impact on the EF in the full sample but a negative influence in the Pacific region. It is found that one unit increase in technological innovation leads to a considerable increase of 1.62% and decreases the EF by 11.7%. As regards the short term, the PAT causes a significantly positive impact in the short run in the full sample and Pacific nations. Additionally, the PAT exerts

TABLE 6 Results of the Granger causality test.

Variable	Full sample		South Asia		Pacific region	
	Long term	Short term	Long term	Short term	Long term	Short term
lnENI → lnEF	−0.0061***	−0.0021	0.0027	−0.0018	−0.0100***	-0.0013
	(0.0021)	(0.0022)	(0.0026)	(0.0027)	(0.0028)	(0.0029)
lnTRI → lnEF	−0.0048*	0.0021	0.0048	0.0009	−0.0060*	0.0022
	(0.0026)	(0.0029)	(0.0056)	(0.0056)	(0.0031)	(0.0034)
lnREC → lnEF	−0.1382***	0.0062	−0.0014	−0.3042*	−0.1555***	0.0142
	(0.0515)	(0.0536)	(0.1767)	(0.1751)	(0.0593)	(0.0618)
lnFD → lnEF	0.0314	0.0083	−0.0682*	−0.0276	0.1385***	0.0284
	(0.0344)	(0.0349)	(0.0352)	(0.0353)	(0.0516)	(0.0527)
lnURB → lnEF	−3.9594***	4.2698***	−2.0333**	1.7432*	−7.4325***	8.1896***
	(0.6900)	(0.7080)	(0.9342)	(0.9664)	(0.9061)	(0.9222)
lnPAT → lnEF	−0.0192	0.0037	0.0188	−0.0006	0.0233	−0.0037
	(0.0117)	(0.0121)	(0.0132)	(0.0130)	(0.0165)	(0.0173)
lnPOD → ln EF	2.0089**	−1.9024**	0.2803	−1.4065	−0.6860	0.9378
	(0.9026)	(0.9257)	(1.2777)	(1.3271)	(1.1601)	(1.1869)
lnEF → lnENI	−1.2449	0.5925	−8.4112**	5.8557	−0.2855	−0.1368
	(1.4103)	(1.4124)	(3.9978)	(4.0608)	(1.4900)	(1.4877)
lnEF → ln TRI	−1.9405*	2.6288**	−2.9261	1.0754	−2.1680*	2.7299**
	(1.0238)	(1.0278)	(1.8438)	(1.9276)	(1.2496)	(1.2512)
lnEF → ln REC	0.1429**	−0.1015	−0.0635	−0.1385*	0.1643**	−0.1031
	(0.0616)	(0.0635)	(0.0777)	(0.0754)	(0.0775)	(0.0802)
lnEF → ln FD	0.0738	0.2228***	0.2929	−0.2186	0.0378	0.2092**
	(0.0813)	(0.0824)	(0.2542)	(0.2511)	(0.0825)	(0.0846)
lnEF → lnURB	0.0052**	0.0056**	−0.0010	0.0164**	0.0062**	0.0039**
	(0.0022)	(0.0023)	(0.0061)	(0.0067)	(0.0039)	(0.0039)
lnEF → ln PAT	−0.2215	0.2396	−1.0740	0.5377	−0.1797	0.4028
	(0.2456)	(0.2470)	(0.7209)	(0.7315)	(0.2571)	(0.2578)
lnEF → lnPOD	−0.0004	−0.0016	−0.0082	0.0145**	0.0025	−0.0018
	(0.0030)	(0.0030)	(0.0061)	(0.0065)	(0.0036)	(0.0036)

Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively. The data in parentheses are standard errors.

no obvious effect on the EF in South Asia. Compared with previous literature reports, Ahmad et al. (2019) and Churchill et al. (2019) found that technological innovation improves the environmental quality, while Ganda (2019) and Khattak et al. (2020) reported that innovations deteriorate the environment. The inconsistencies in the results are largely due to differences in the chosen proxy metrics. It may also be that the number of environmental protection technologies is still insufficient, and the practical transformation of green technologies still takes a long time.

The POD has a significantly negative effect on the EF in the long term in the full sample, while it shows an inconsiderable influence in the remaining regions and time periods. It implies that a 1% increase in population density significantly decreases the EF by 72.5% in the long run in the full sample. The current findings are opposed to those obtained by Sharma et al. (2021) in their research. They argued that the population density is positively correlated with the ecological footprint. The concentration of the population brings about the improvement of ecological quality, which not only shows the enhancement of the population's awareness of environmental protection but also reflects the significant scale effect of energy usage.

The coefficient statistics of the error correction term ECM are all significantly negative, and they are −0.469, −0.375, and −0.342 for the full sample, South Asia, and Pacific region, respectively, indicating that the model has a reverse adjustment mechanism, and the nonequilibrium error of the model would be corrected. In addition, in order to ensure the scientificity of the study, we conducted a robustness test by replacing the control variables, and the test results showed that the conclusions in this study were robust.

4.4 Granger causality test

The Granger causalities of the long run and short run have been checked, and the results are given in Table 6.

As for the full sample, there is a one-way significantly negative causality from ENI to the EF in the long term. Results reveal that there is a bidirectional negative causal relationship between TRI and the EF in the long run. The results further show that there are substantial and negative causalities running from REC and URB to the EF and positive causality running from the EF to REC and URB in the long run. There exists a significantly unidirectional long-term causality running from POD to the EF, and there is no considerable bidirectional causal relationship between FD and EF and PAT and EF in the long term. For short term, it is found that there is one-way positive causality from the EF to TRI and FD, and the bidirectional positive causal relationship has been discovered between URB and EF. In addition, significant negative short-run causality runs from POD to EF as well.

As regards South Asia, there is unidirectional significantly negative causality from EF to ENI and from FD and URB to EF in the long term. The results imply that there is a two-way negative causal relationship between REC and EF, while a positive causal relationship exists between URB and EF. Moreover, there is a one-way positive causality running from EF to POD.

With regard to the Pacific region, there exists a significantly negative long-term causality running from ENI to EF, and a positive causal relationship running from FD to EF. The results further demonstrate that there is a bidirectional negative nexus between TRI and EF. Additionally, there is a significant and negative causality running from REC and URB to EF while a positive causality runs from EF to REC and URB in long term. Concerning the short term, there are considerable positive causalities running from EF to TRI and FD. Furthermore, a two-way positive causality exists between URB and EF as well.

In the aforementioned presentation, the one-way negative causal relationship between ENI and EF and the negative feedback effect of TRI and EF reflect that PPPI in energy and transportation will have positive externalities to the ecological environment in the long run. At the same time, the causal relationship between REC and EF also suggests that increasing the use of renewable energy would be beneficial to ecological sustainability, and Destek and Sarkodie (2019) and Naqvi et al. (2020) revealed the same findings. The long-term impact of FD on different regions is not consistent, which also shows that the support of capital for environmental protection varies with the level of financial development. There is positive feedback between URB and EF in the short-term but negative feedback in the long-term, which conveys the large-scale effect of urbanization on the utilization of resources in the future. In the full sample, POD has a positive effect on the environment in in the short term but the opposite in the long term, proving that the current population density will reach the peak value in terms of ecological sustainability.

5 Conclusion and recommendations

The current study investigates the connection of PPPI among energy and transport, financial development, renewable energy consumption, and ecological footprint, by incorporating technological innovation, urbanization, and population density in the case of South Asia and the Pacific region from 1990 to 2017. In doing so, we applied the ARDL model and panel Granger causality test to examine the relationship between related variables. To the best of our understanding, no previous research has examined this interconnection in South Asia and the Pacific region. The findings of our study can be helpful for policymakers in developing countries to formulate policies for economic and ecologically sustainable development.

As regards the full sample, the empirical results demonstrated that PPPI in energy and transport, as well as urbanization, has a significantly positive effect on the EF in the long run. The population density has a negative effect on the EF in the long term. Financial development and technological innovation exert a substantial and positive effect on the EF in the short run. Renewable energy consumption causes a significant and negative impact on the EF in both time periods. In addition, according to the panel Granger causality test, PPPI in energy and transport, renewable energy, and urbanization is negatively related to the EF in the long run, while population density plays a positive role. Urbanization and population density have a positive and negative influence on the EF in the short term, respectively. For South Asia, financial development and urbanization have a positive and negative impact on the EF in the long term, respectively. In addition, renewable energy and financial development play a negative role in the EF in the short run. Results also indicate that there is a unidirectional significantly negative causality from financial development and urbanization to the EF in the long term. There is a negative feedback effect between renewable energy and EF, and a positive feedback effect between urbanization and EF in the short term. As for the Pacific region, PPPI in energy and transport and financial development encourages environmental degradation in the long term. Technological innovation has shown a negative influence in the long term but a positive impact in the short run. PPPI in energy and transport, renewable energy, and urbanization has a negative causal relationship with the EF, while financial development has a positive relationship in the long run. There is also a positive feedback effect between urbanization and EF in the short term.

Thus, according to the analysis, we propose some related policy recommendations. First, policymakers in various countries should encourage public–private partnerships to invest in renewable energy and green technologies to expand the horizontal diffusion and vertical penetration of alternative energy and low-carbon goods in society and the economy. Second, it requires increasing the proportion of renewable energy used in the energy mix in areas such as industrial, transportation, and household sectors so as to promote a low-carbon and circular economy. Moreover, efforts to enforce the widespread use of renewable energy must continue, e.g., nuclear energy, wind, tidal, and biomass, which may reduce the intensity of carbon emissions. Third, there is an urgent need to guide the flow of funds in the financial market to green and environmental protection enterprises and projects, and the government also needs to provide financial subsidies and tax incentives to such enterprises. Finally, rational urbanization also needs to be ensured in the form of strengthening urban governance, appreciating road and engineering design, promoting high-quality green development, and encouraging the economy to transform from factor- to innovation-driven.

The limitation of this study is that due to the lack of data, our study sample is not large enough to include more developing countries and it also limits us to include more key variables in the model. In the future, our research can try to add more proxy variables to describe the environment, and we can draw more specific and targeted suggestions in terms of environmental improvement. In addition, it would be intriguing to add as a potential research direction the consideration of carbon footprint as a dependent variable.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YW: conceptualization and writing—original draft; CQ: formal analysis and software; CG: visualization and data curation; PS: methodology, supervision, and investigation; and DY: 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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