Ecological footprint, public-private partnership investment in energy, and financial development in Brazil: a gradual shift causality approach

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Abstract
The present study assesses the effect of public-private partnerships in energy and financial development on Brazil’s ecological footprint and also takes into account the role of renewable energy and economic growth using data spanning from 1983 to 2017. The study utilized several techniques including autoregressive distributive lag (ARDL) and dynamic ordinary least square (DOLS) to examine the relationship between ecological footprint and the determinants, while the gradual shift causality test was utilized to capture the causal linkage between the series in the presence of a single structural break. The outcomes of the Maki co-integration test revealed evidence of a long-run association among the variables of interest. Furthermore, the results of the ARDL and DOLS tests revealed that economic growth and public and private investment in energy increase environmental degradation, while it is mitigated by both renewable energy and financial development. Moreover, the gradual shift causality test revealed a bidirectional causal linkage between ecological footprint and economic growth. The present study recommends the establishment of a forum that will foster public and private partnerships to enhance communication, which will promote collaboration on new initiatives involving green technological innovations.

Keywords Economic growth • Ecological footprint • Financial development • Public-private partnership in energy • Renewable energy consumption • Brazil
Introduction

The effect of the strain imposed by the human exploitation of services and goods on nature is linked to current environmental degradation questions, economic setbacks, global warming, and ecological disruptions (Adebayo and Kirikkaleli 2021). In response, global recognition and the drive for sustainable growth in the context of environmental protection (sustainability) have become a global concern for environmentalists and economists. The direct and indirect impacts of human activities have attracted increased attention to the ecological responses from economic growth, population dynamics, energy usage, and several other key factors (Ramzan et al. 2021; Tufail et al. 2021; Kirikkaleli and Adebayo 2021; Zhang et al. 2021; Awosusi et al. 2021). In addition to utilizing carbon dioxide emissions (CO_2) to account for environmental quality, biocapacity and ecological footprint (EP) accounting have been introduced to include wide viewpoints. Based on the findings of the Intergovernmental Panel on Climate Change (IPCC) study on “Climate change, soil erosion, habitat loss, sustainable land use, food protection and greenhouse gases (GHGs) flows in terrestrial ecosystems” (IPCC, 2017), it is clear that sustained efforts are being made to reduce the pressure on global ecological capability.

Overall, given the economic growth of major economies such as Germany, the USA, India, China, Japan, and several EU nations, these influences continue to have importance for environmentalists, governments, and policymakers in these nations. With regard to Brazil’s move towards sustainable growth and environmental sustainability, appropriate strategies are being introduced with the aim of achieving the Sustainable Development Goals (SDGs). For example, Brazil’s revised 2030 climate change target includes a commitment to reduce GHG emissions by at least 6%. Brazil’s long-term aim is to transfer the dependence of its energy networks to alternative energy sources and contribute to the efforts to achieve the decarbonization of the world economy by the end of the century. Brazil is one of the big five developing “BRICS” markets and has the sixth-highest level of GHG emissions globally. Brazil has raised the intensity of its climate action in the run-up to the Paris climate change meeting.

Nevertheless, the significant developments in Brazil, including presidential impeachment, the pervasive economic crisis, and the massive government corruption controversy, have contributed to fears that efforts to mitigate climate change and transform energy policy are losing momentum. After EP accounting was developed by Wackernagel and Rees (1998), it has continuously been utilized to determine environmental degradation. Taking into account that EP measures the effect of human actions on the available global resources (Global Footprint Network, GFN, 2019), the analysis of the complexities of the EP will provide more detail on the formulation of policy. Given the significance of mitigating the effect of human activity on the environment, various studies have further investigated the variety of environmental viewpoints within the EP framework (Ahmed et al. 2019; Kassouri and Altuntas 2020; Langnel and Amegavi 2020). Specifically, Kassouri and Altuntas (2020) and Langnel and Amegavi (2020) both supported the environmental Kuznets curve (EKC) hypothesis. The research used EP instead of traditional CO_2 as a proxy for environmental sustainability to test the EKC hypothesis’ relevance. While introducing other determinants such as energy consumption and financial development, both studies established an inverted U-shaped association between GDP and the EP.

From a wider perspective, EP has been explored together with other economic indicators such as financial development, renewable energy, and economic growth (Kirikkaleli et al. 2020; Pata and Yilanci 2020; Saud et al. 2020; Ahmed et al. 2021; Ahmed et al. 2019; Kassouri and Altuntas 2020; Langnel and Amegavi 2020; Ansari et al. 2020). For instance, Saud et al. (2020) and Ansari et al. (2020) found a negative association between EP and GDP, while Rudolph and Figge (2017), Ahmed et al. (2019), Kirikkaleli et al. (2020), and Pata and Yilanci (2020) found a positive interconnection between the two variables. Regarding the link between EP and renewable energy, Danish and Khan (2019), Charfeddine (2017), and Yilanci and Pata (2020) established a negative relationship between renewable energy and EP. Also, the study of Kassouri and Altuntas (2020), Godil et al. (2020), and Ahmed et al. (2021) established a positive relationship between EP and financial development, while the study of Ahmed et al. (2019) Kirikkaleli and Adebayo (2021) established a negative relationship between financial development and EP.

Questions still remain in terms of the role of public-private investment in energy, GDP growth, renewable energy use, and financial development in mitigating climate change. Nevertheless, the complexity of these variables due to the varying economic systems and environmental policies in different nations makes it extremely difficult to agree on climate change determinants across countries. The empirical evidence provided in this report is therefore helpful in formulating policies relating to climate change. The abovementioned factors provide the motivation for studying the dynamic effect of public-private investment in energy, financial development, economic growth, and renewable energy on the EP in Brazil utilizing current econometric techniques. To expand on the studies of Alola et al. (2019) and Kirikkaleli et al. 2020, the study utilized yearly data for the period between 1984 and 2017. In addition to the ongoing research, the paper utilizes EP rather than CO_2 because Brazil is already striving to address ecological deficit issues (Global Footprint Network, GFN, 2019). Also, we incorporate public-private investment in energy in the framework in order to assess its impact on the EP.
The study’s remaining sections are ordered as follows: Sect. 2 presents a summary of past studies, and Sect. 3 illustrates the data and methodology. This is followed by the data analysis and discussion in Sect. 4, and the conclusion and policy path are presented in Sect. 5.

**Literature review**

This research examines the interaction between renewable energy and GDP on ecological footprint by considering the role of financial development and public-private partnership investment in energy (PPI) in Brazil. In China, Khan et al. (2020) explored the effects of PPI on environmental degradation using quarterly data ranging from 1990Q1 to 2017Q1. The empirical result shows that PPI exerts a detrimental effect on environmental quality. Using the BARDL (bootstrapping autoregressive distributed lag modeling), Shahbaz et al. (2020) also revealed a similar outcome in China. In India, Kirikkaleli and Adebayo (2021) also examined the interaction between PPI and environmental degradation. The study outcome revealed that the interaction between PPI and environmental deterioration is positive. Shahbaz et al. (2018) also explored the association between PPI and environmental degradation for France by using research & development to indicate public investment in energy (PI). The result shows a negative connection between PPI and environmental degradation in France. Furthermore, a one-way causal association from PPI to environmental degradation. Waqih et al. (2019) also followed a similar concept using foreign direct investment as a metric for private investment for the South Asian Association for Regional Cooperation (SAARC) region. The panel data was utilized spanning from 1986 to 2014, using the panel autoregressive distributed lag (PARDL) and PFMOLs. Results showed the private investment has a positive effect on the environmental deterioration in the SAARC region. Studies incorporating the PPI into the environmental literature are limited.

In Turkey, Godil et al. (2020) explored the relationship between ecological footprint and financial development utilizing data ranging from 1986 to 2018. The empirical finding shows that financial development impacts ecological footprint positively. Sabir and Gorus (2019) found a positive association between ecological footprint and GDP between 1975 and 2017 in South Asian countries. Kirikkaleli et al. (2020) employed the dual adjustment approach to scrutinize the impact of GDP on the ecological footprint for 32 years (1985–2017). Results showed that economic growth influences ecological footprint positively. In G7 countries, Pata and Yilanci (2020) scrutinized the interconnection between financial development and economic growth on ecological footprint covering 1980 to 2015. The authors asserted that financial development will be an effective tool to regulate ecological footprint in three countries among G7 countries. However, economic growth contributes to ecological footprint. Wang et al. (2020) explored the interconnection between GDP and ecological footprint from 1980 to 2016, and the results showed that economic growth tends to induce ecological footprint. Saud et al. (2020) explored the effect of economic growth and financial development on ecological footprint, and their findings revealed that financial development and GDP Grangers cause ecological footprint. The study of Ahmed et al. (2021) found that economic growth and financial development positively impact Japan’s ecological footprint between 1971 and 2016.

Moreover, the research of Rudolph and Figge (2017) established that economic growth positively influences ecological footprint in 146 nations between 1981 and 2009. Ahmed et al. (2019) examined the link between economic growth and ecological footprint in Malaysia between 1971 and 2014. Their empirical result shows that economic growth triggers ecological footprint, while financial development decreases ecological footprint. Kassouri and Altuntas (2020) explored the association between ecological footprint and financial development in 13 MENA nations covering the period between 1990 and 2016. Their empirical outcomes showed a positive association between ecological footprint and financial development. The study of Langnel and Amegavi (2020) for Ghana found a positive interaction between economic growth and ecological footprint, while the Granger causality test revealed a two-way causal connection between economic growth and ecological footprint. Ansari et al. (2020) investigated the effect of economic growth on the ecological footprint in the Gulf Cooperation Council nations between 1991 and 2017. Their empirical outcomes show that economic growth stimulates ecological footprint. Hassan et al. (2019) scrutinized the connection between economic growth and ecological footprint in Pakistan between 1971 and 2014. The empirical evidence shows a positive interconnection and no causal link between ecological footprint and GDP. Ibrahimi and Hanafy (2020) probed into the interconnection of economic growth and ecological footprint in Egypt covering the period 1971 to 2014 employing FMOLS, dynamic ordinary least square (DOLS), and Toda–Yamamoto approaches. Results revealed that economic growth positively impacts the ecological footprint. Furthermore, GDP Granger causes ecological footprints. The work of Udembra (2020) unveiled a positive connection between GDP and ecological footprints between 1981 and 2018 in Nigeria. Furthermore, there is a one-way causal interconnection from economic growth to ecological footprints.

Alola et al. (2019) explored the connection between renewable energy use and GDP on ecological footprints for 16 EU countries.
nations. The effects of renewable energy and economic growth on ecological footprint showed to be positive and negative, respectively. Usman et al. (2020b) examined the interconnection between economic growth and ecological footprints spanning between 1971 and 2014 in Brazil and using the FMOLS and DOLS in capturing long-run association, while the VECM was used in establishing a causal link. FMOLS and DOLS outcomes showed that economic growth and ecological footprints are positively related, but there is no causal link between ecological footprints and economic growth. Nathaniel and Khan et al. (2020) scrutinized the role of economic growth and renewable energy on the ecological footprint in ASEAN countries, using data ranging between 1990 and 2016. The empirical outcome showed that economic growth increases ecological footprints, meanwhile, renewable energy contributes to improving the environment’s quality. Moreover, a feedback causality exists between ecological footprints and renewable energy.

The study of Usman et al. (2021) on the 15 largest emitting nations used the panel data covering the period 1990 to 2017 to probe into the connection between renewable energy, GDP, and financial development on ecological footprint. The PARDL method’s outcome shows financial development and renewable energy contribute to environmental quality, while GDP contributes to environmental degradation. The Granger causality test reveals a feedback causal interconnection between ecological footprint and its regressors. Utilizing the quarterly data spanning from 1985Q1 to 2014Q4, Usman et al. (2020a) explored the effect of renewable energy, GDP, and financial development using the autoregressive distributive lag (ARDL) method. The empirical outcome suggested that renewable energy and GDP negatively impact ecological footprint, but the financial development positively affects environmental degradation and a one-way causal interconnection from ecological footprint to financial development and real output. Destek et al. (2018) established a U-shaped interconnection between GDP and ecological footprint, while renewable energy increases the environment’s quality in EU countries between 1980 and 2013. Danish and Khan (2019) examined the linkage between renewable energy and GDP on ecological footprint using the panel data covering 1992 to 2016 for BRICS economies, while the empirical results revealed that renewable energy decreases environmental deterioration, but economic growth increases ecological footprints. Using the Markov Switching model, Charfeddine (2017) scrutinized the interconnection between financial development and economic growth on Qatar’s ecological footprint, spanning between 1970 and 2015. The empirical results indicated that financial development negatively relates to ecological footprint, but economic growth positively relates to environmental degradation. The summary of reviewed studies is presented in Table 1.

Though several studies have been conducted, however, their findings are mixed. These contradicting conclusions might be attributed to differences in techniques employed, country or countries of study, and time frame. Furthermore, no existing studies have incorporated public-private partnership investment in energy for the case of Brazil. Thus, this present study closes the gap in existing studies. The impact of public-private partnership investment in energy is critical in developing an effective environmental strategy to address the challenge of climate change. However, the majority of the research on the effects of public-private partnership investment in energy on environmental deterioration has focused only on CO2 emissions; however, it cannot give a comprehensive picture of this huge dilemma to talk about climate change. All these serve as a cause to investigate the effect of public-private investment in energy, GDP growth, renewable energy use, and financial development on ecological footprints in Brazil.

**Data, theoretical rationale, and methodology**

**Data**

In this research, the long-run and causal effect of economic growth, renewable energy, public-private partnership investment in energy, and financial development on ecological footprints in Brazil was explored. This study utilized the times series data spanning between 1984 and 2017. The study sourced the ecological footprints from the Global Footprint Network (GFN, 2021) database; public-private partnership investment in energy and economic growth were derived from the World Bank database (World Bank, 2020). The renewable energy use was sourced from the British petroleum database, whereas the financial development index was obtained from the International Monetary Fund (IMF, 2019). The description, unit of measurement, and source of the variable used are presented in Table 2. The variables’ natural log was taken to address the heteroskedasticity problems, reduce skewness, and reveal the outcome as elasticities. Equations 1 and 2 are the economic and econometric models, respectively, guarding this study.

\[
EP_t = f(GDP_t, PPI_t, REN_t, FD_t)
\]  

\[
EP_t = \beta_0 + \beta_1 GDP_t + \beta_2 PPI_t + \beta_3 REN_t + \beta_4 FD_t + \varepsilon_t
\]  

As mentioned earlier, EF denoted ecological footprints, GDP denotes economic growth, FD, REN, and PPI denote financial development index, renewable energy use, and public-private partnership investment in energy correspondingly. Parameters of these variables were denoted as \(\beta_0, \beta_1, \beta_2, \beta_3, \text{ and } \beta_4\). The subscript of \(t\) denotes the period (1984–2017), while the residual error of the model was represented as \(\varepsilon\).
| Investigator(s) | Timeframe | Nation(s) | Variable used | Technique(s) | Findings |
|----------------|-----------|-----------|---------------|--------------|----------|
| Godil et al. (2020) | 1986 to 2018 | China | EP, TU, GLO, and FD | QARDL | FD → EP (+) |
| Kirikkaleli et al. (2020) | 1985 to 2017 | Turkey | EP, TR, EC, GLO, and GDP | Dual adjustment approach | GDP → EP (+) |
| Pata and Yilanci (2020) | 1980 to 2015 | G7 countries | EP, FD, EC, GLO, GDP | Fourier T-Y causality | GDP → EP (+) |
| Saud et al. (2020) | 1990 to 2014 | OBORI nations | EP, FD, TR, EC, GLO, GDP | PARDL, DH Granger causality | FD ↔ EP |
| Ahmed et al. (2021) | 1971 to 2016 | Japan | EP, FD, POP, EC, GLO, GDP | Non-linear ARDL | GDP → EP (+) |
| Rudolph and Figge (2017) | 1981 to 2009 | 146 nations | EP, GDP, GLO | Driscoll and Kraay | GDP → EP (+) |
| Ahmed et al. (2019) | 1971 to 2014 | Malaysia | EP, POP, EC, GLO, GDP | Bayer and Hanck co-integration test and ARDL | GDP → EP (+) |
| Kassouri and Altıntaş (2020) | 1990 to 2016 | 13 MENA nations | EP, FD, HD, OIL, URB, GLO, GDP | IFE and CCEMG | GDP → EP (+) |
| Langnel and Amegavi (2020) | 1971 to 2016 | Ghana | EP, GLO, EC, Urban | ARDL | GDP → EP (+) |
| Ansari et al. (2020) | 1991 to 2017 | GCC nations | EP, GLO, EC, GDP | FMOLS, DOLS, westerland co-integration | GDP → EP (+) |
| Wang et al. (2020) | 1980 to 2016 | G7 countries | EP, NR, GLO, BIO, GDP | Bootstrap panel co-integration, DSUR estimator, D-H Granger causality test | GDP → EP (+) |
| Hassan et al. (2019) | 1971 to 2014 | Pakistan | EP, GDP, HD, URB | Bayer-Hanck co-integration, ARDL | GDP → EP (+) |
| Ibrahiem and Hanafy (2020) | 1971 to 2014 | Egypt | EP, POP, GLO, EC, GDP | FMOLS, DOLS, and T-Y approach | GDP → EP (+) |
| Udemba (2020) | 1981 to 2018 | Nigeria | EP, GDP, Agric, FDI, EC, POP | ARDL | GDP → EP (+) |
| Alola et al. (2019) | 1997 to 2014 | 16 EU nations | EP, REN, EC, GDP, TR, FR | PMG-ARDL, D-H Granger causality | GDP → EP (+) |
| Usman et al. (2020b) | 1971 to 2014 | Brazil | EP, EC, Demo, GDP, GLO | FMOLS, DOLS, VECM Granger causality | GDP → EP (+) |
| Nathaniel and Khan et al. (2020) | 1990 to 2016 | ASEAN countries | EP, GDP, REN, TR, URB, EC | PMG-ARDL, D-H Granger causality | GDP → EP (+) |
| Usman et al. (2021) | 1990 to 2017 | 15 large emitting nation | EP, FD, REN, GDP | PARDL | GDP → EP (+) |
| Usman et al. (2020a) | 1985Q1 to 2014Q4 | USA | EP, REN, GLO, FD, GDP | ARDL, VECM Granger causality test | GDP → EP (+) |
| Yilanci and Pata (2020) | 1965 to 2016 | China | EP, EC, GDP | Fourier ARDL | GDP → EP (+) |
| Destek et al. (2018) | 1980 to 2013 | EU countries | EP, GDP, REN, EC, TR | PMG-ARDL, FMOLS, DOLS | GDP → EP (+) |
Table 1 (continued)

| Investigator(s) | Timeframe | Nation(s) | Variable used | Technique(s) | Findings |
|-----------------|-----------|-----------|---------------|--------------|----------|
| Danish and Khan (2019) | 1992 to 2016 | BRICS economies | EP, URB, REN, NR, GDP | PMG-ARDL, FMOLS, DOLS | TR → EP(-) EC→ EP(+), GDP→ EP(+), REN → EP(-) NR→ EP URB ↔ EP GDP ↔ EP(+) FD→ EP(-) EC↔ EP(+). |
| Charfeddine (2017) | 1970 to 2015 | Qatar | Markov switching model | EP, FD, GDP, EC, TR, | |

| Code | Description | Unit of measurement | Sources |
|------|-------------|---------------------|---------|
| EP   | Ecological footprints | Global hectare of land | Global Footprint Network (GFN, 2021) |
| PPI  | Public-private partnership investment in energy | Current US$ | World Bank (2021) |
| GDP  | Economic growth | GDP per capita constant US$, 2010 | BP (2021) |
| REN  | Renewable energy | Renewables per caput (KWh) | IMF (2021) |
| FD   | Financial development | Broad measure of financial development | |

Theoretical rationale

The ecological footprint is a distinctive metric of environmental quality in other natural areas required to promote economic growth. The availability of water resources, forest reserves, agricultural or grazing land, and fresh air is part of the natural areas derived through ecological footprints. These natural areas’ capacity depends greatly on the eutrophication potential, terrestrial acidification, and ecotoxicity of the ecosystem and the environment. The ecological footprint is a more comprehensive proxy for measuring environmental degradation because it consists of CO2 emission, grazing land, fishing grounds, cropland, and forest products, compared to previous literature that utilizes only CO2 emission. On this premise, the ecological footprint was adopted to measure environmental degradation. Ecological footprints provide a bigger definition of environmental quality compared to CO2 emission that is arguably flawed. An increase in the growth of the economy occasions the rise of energy demand, which contributes to environmental deterioration (Charfeddine and Mrabet 2017; Wang and Dong 2019; Bello et al. 2018; Destek and Sarkodie 2019; Hassan et al. 2019; Kirikkaleli et al. 2020). Moreover, economic expansion and ecological footprint are positively related. Therefore, GDP is expected to cause an increase in environmental deterioration ($\beta_1 = \frac{\Delta EP}{\Delta GDP} > 0$). Following the study of Khan et al. (2020) and Kirikkaleli and Adelbayo (2021), this study incorporates public-private partnership investment in energy into this study’s model. We anticipate that there will be a negative association between ecological footprint and public-private partnership investment in energy. Thus, public-private partnership investment in energy should reduce environmental degradation. ($\beta_2 = \frac{\Delta EP}{\Delta PPI} < 0$), or ($\beta_2 = \frac{\Delta EP}{\Delta PPI} > 0$) if PPI is not eco-friendly. Renewable energy use was incorporated into the framework, which agrees with Murshed et al. (2021), Wang and Dong (2019), and Usman et al. (2021). The interaction between renewable energy and ecological footprint is expected to be negative ($\beta_3 = \frac{\Delta EP}{\Delta REN} < 0$). Thus, environmental quality will be improved by renewable energy use. Following the study of Destek and Sarkodie (2019), Naqvi et al. (2020), Chen et al. (2019), Usman and Hammar (2020), and Yao et al. (2021), we added financial development to our empirical model. It is anticipated that the interaction between financial development and ecological footprints is negative ($\beta_4 = \frac{\Delta EP}{\Delta FD} < 0$).

Methodology

ADF and PP unit root tests developed by Said and Dickey (1984) and Phillips and Perron (1988) were used to determine the variable’s stationarity properties. As stated by Adebayo and Akinsola (2021) and Wang et al. (2021),
the conventional unit root outcome is usually inconsistent because they do not put into consideration the structural break(s) during estimation. For this purpose, the study used the Zivot and Andrews (2002) unit root test, which can detect at least one structural break in the series, which was defined as follows:

Model A: \( \Delta y = \sigma + \bar{y}_{t-1} + \beta t + \gamma DU_t \) 
\[ + \sum_{j=1}^{\tau} d_j \Delta y_{t-j} + \varepsilon_t \]  
(3)

Model B: \( \Delta y = \sigma + \bar{y}_{t-1} + \beta t + DT_t + \sum_{j=1}^{\tau} d_j \Delta y_{t-j} + \varepsilon_t \)  
(4)

Model C: \( \Delta y = \sigma + \bar{y}_{t-1} + \beta t + DT_t \gamma DU_t \) 
\[ + \sum_{j=1}^{\tau} d_j \Delta y_{t-j} + \varepsilon_t \]  
(5)

where \( DU_t \) denotes the mean shift of the dummy variable, which occurs at possible break-date (TB); \( DT_t \) denotes the trend shift of the corresponding variable used. Formally,

\[ DU_t = \begin{cases} 1 \ldots \ldots \ldots \text{if } t > TB \text{ and } DU_t \\ 0 \ldots \ldots \ldots \text{otherwise} \end{cases} \]

This study employed the Maki co-integration test to examine the long-run association among the variables of interest. However, one of the uniqueness of this technique is capturing at least five structural breaks simultaneously. The four regression models recommended by Maki (2012) are stated as follows:

Level shift

\[ Y_t = \rho + \sum_{i=1}^{\tau} \rho_i D_{it} + \theta^t Z_t + \varepsilon_t \]  
(7)

Level shift with the trend

\[ Y_t = \rho + \sum_{i=1}^{\tau} \rho_i D_{it} + \theta^t Z_t + \tau t + \sum_{i=1}^{\tau} \theta_i D_{it} + \varepsilon_t \]  
(8)

Regime shifts

\[ Y_t = \rho + \sum_{i=1}^{\tau} \rho_i D_{it} + \theta^t Z_t + \sigma t + \sum_{i=1}^{\tau} \theta_i D_{it} + \varepsilon_t \]  
(9)

Trend and regime shifts

\[ Y_t = \rho + \sum_{i=1}^{\tau} \rho_i D_{it} + \theta^t Z_t + \sigma t + \sum_{i=1}^{\tau} \sigma_i D_{it} + \varepsilon_t \] 
\[ + \sum_{i=1}^{\tau} \theta_i D_{it} + \varepsilon_t \]  
(10)

where: \( Y_t \) depicts \( EF \) and \( Z_t \) depicts its regressors.

In testing for the long-run association among the variables of interest, the ARDL (autoregressive distributive lag) bound testing approach initiated by Pesaran et al. (2001) was utilized as a robustness test for the Maki co-integration test. This technique has the following advantages over the conventional co-integration methods in the following ways: (i) it accommodates variables with different integrated order; (ii) endogeneity and serial correlation problem are addressed by selecting the appropriate lag length; (iii) it produces accurate estimation for small sample size; (iv) it also allows the short and long-run estimates concurrently. These advantages make ARDL the most suitable econometric technique for this study. The ARDL model was defined as follows:

\[ \Delta EP_t = \theta_0 + \sum_{i=1}^{t} \theta_1 \Delta EP_{t-i} + \sum_{i=1}^{t} \theta_2 \Delta PPI_{t-i} \] 
\[ + \sum_{i=1}^{t} \theta_3 \Delta GDP_{t-i} + \sum_{i=1}^{t} \theta_4 \Delta REN_{t-i} + \sum_{i=1}^{t} \theta_5 \Delta FD_{t-i} + \beta_1 \Delta EP_{t-1} + \beta_2 PPI_{t-1} \] 
\[ + \beta_3 \Delta GDP_{t-1} + \beta_4 \Delta REN_{t-1} + \beta_5 \Delta FD_{t-1} + ECT_{t-1} + \varepsilon_t \]  
(11)

where: \( \theta \) and \( \beta \) denote the short and long-run parameters respectively, \( \Delta \) and \( \varepsilon \) indicate the first difference operator and error term respectively. The null hypothesis \((H_0)\) denotes the there is no co-integration, but the alternative hypothesis \((H_a)\) denotes the presence of co-integration, which is illustrated in Eqs. 12 and 13. When the lower and upper bond critical values are greater than the F-statistics, the null hypothesis will not be rejected.

\[ H_0 = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = 0 \] 
(12)

\[ H_a = \theta_1 \neq 0 \] 
(13)

However, the uses of several diagnostic tests were undertaken to check for the reliability and validity of this model.

The present study utilized the dynamic ordinary least square (DOLS) approach initiated by Stock and Watson (1993) to confirm the ARDL long-run coefficients. The DOLS allows asymptotic coherence by taking into account the effect of serial correlation.

The present research employed the Fourier Toda-Yamamoto causality test developed by Nazlioglu et al. (2016) to examine the causality between EP and GDP, PPI, GDP, REN, and FD. This technique allows structural breaks (gradual and smooths changes) in the analysis of causality. These breaks were taken into account using a Fourier Granger causality test with a single frequency (SF) and cumulative frequencies (CF), respectively, known as Fourier
Fourier approximation is defined in Eq. (11) to capture the

\[ y_t = \sigma(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+d_{\text{max}}} y_{t-(p+d_{\text{max}})} + \varepsilon_t \]  

(14)

where: \( y_t \) depicts EP, PPI, GDP, REN, and FD; \( \sigma \) depicts intercept; \( \beta \) depicts coefficient matrices; \( \varepsilon \) depicts error term.

Fourier approximation is defined in Eq. (11) to capture the structural shifts, as follows:

\[ \sigma(t) = \sigma_0 + \sum_{k=1}^x \gamma_{1k} \sin \left( \frac{2\pi kt}{T} \right) + \sum_{k=1}^x \gamma_{2k} \cos \left( \frac{2\pi kt}{T} \right) \]  

where: the number of frequencies was depicted as \( x \); \( \gamma_{1k} \) measures the size of the frequency, while \( \gamma_{2k} \) measures changes in frequency. Substitute Eq. (15) in Eq. (14), the Fourier Toda-Yamamoto causality with cumulative frequencies (CF) is defined as

\[ y_t = \sigma_0 + \sum_{k=1}^n \gamma_{1k} \sin \left( \frac{2\pi \gamma_1 T}{T} \right) + \sum_{k=1}^n \gamma_{2k} \cos \left( \frac{2\pi \gamma_2 T}{T} \right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d_{\text{max}}} y_{t-(p+d_{\text{max}})} + \varepsilon_t \]  

(16)

where: the approximation frequency was represented as \( k \). Equation (17) defines the single-frequency components as

\[ \sigma(t) = \sigma_0 + \gamma_1 \sin \left( \frac{2\pi \gamma_1 T}{T} \right) + \gamma_2 \cos \left( \frac{2\pi \gamma_2 T}{T} \right) \]  

(17)

By substituting Eq. (17) into Eq. (1), the Fourier Toda-Yamamoto causality with single frequencies (SF) is defined in Eq. (1) as

\[ y_t = \sigma_0 + \gamma_1 \sin \left( \frac{2\pi \gamma_1 T}{T} \right) + \gamma_2 \cos \left( \frac{2\pi \gamma_2 T}{T} \right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t. \]  

(18)

Hence, the Fourier Toda-Yamamoto causality hypothesis will be tested utilizing the Wald statistic. The null hypothesis of non-causality is zero (\( H_0: \gamma_1 = \beta = 0 \)) against the alternate hypothesis (\( H_0: \gamma_1 \neq \beta \neq 0 \)).

### Finding and discussion

Table 3 presents the statistical features (a measure of central tendencies and dispersion) of the series. The considered variables are highly skewed (\( -1 < \text{Skewness} < 1 \)), and the kurtosis of all series was platykurtic in nature except for PPI has a leptokurtic nature. All the series are normally distributed around the mean except PPI, which was confirmed by the Jarque-Bera probability value.

Before inspecting the co-integration among the variable used, it is important to verify the stationary characteristics of the considered variables. The problem of spurious regression is evident when the data are non-stationary (Granger et al. 1974) and to check whether any of the variables used are integrated at I(2). Meanwhile, the ARDL restricts the use of variables integrated at I(2). The conventional unit roots (ADF and PP) were depicted in Table 4, whose outcome reveals that no variable is integrated at I(2), but all the considered series are integrated at I(1). As mentioned earlier, conventional unit root outcomes are often inconsistent because they do not incorporate the structural break(s) during estimation. For this purpose, the study used the Zivot and Andrews (2002) unit root test, which was described in Table 5. The outcome shows all variables are integrated at I(1) except PPI that is integrated at level. Hence, the considered variables are integrated in mixed order.

Conventional co-integration techniques such as Johansen (1991) and Engle and Granger (1987) possess the inability to

### Table 3 Descriptive statistics

|        | EP  | FD  | GDP | REN | PPI |
|--------|-----|-----|-----|-----|-----|
| Mean   | 4.94E+08 | 0.420911 | 9402.717 | 5.2738 | 5.89E+09 |
| Median | 4.96E+08 | 0.421182 | 8803.741 | 5.2773 | 3.72E+09 |
| Maximum| 6.06E+08 | 0.633827 | 11993.48 | 6.8552 | 2.97E+10 |
| Minimum| 3.62E+08 | 0.160204 | 7442.972 | 3.5554 | 730000.00 |
| Std. dev. | 6599353.09 | 0.156039 | 1404.898 | 1.0062 | 7.11E+09 |
| Kurtosis | 2.287197 | 1.697691 | 1.904547 | 1.8827 | 5.486510 |
| Skewness | -0.067958 | -0.122120 | 0.584863 | -0.0521 | 1.586153 |
| Jarque-Bera | 0.745961 | 2.487186 | 3.638393 | 1.7837 | 23.01552 |
| Probability | 0.688679 | 0.288346 | 0.162156 | 0.4098 | 0.000010 |

### Table 4 Unit root without break

|       | ADF | PP |
|-------|-----|----|
| Variables | I(0) | I(1) | I(0) | I(1) |
| EF    | -2.8214 | -5.5957* | -2.7994 | -5.5957* |
| GDP   | -2.1667 | -4.1198** | -1.8666 | -4.0983** |
| REN   | -1.9865 | -5.4813* | -1.9865 | 5.4900* |
| PPI   | -2.1280 | -5.8105* | -2.1334 | -8.2278* |
| FD    | -2.5490 | -5.3930* | -2.8193 | -5.3930* |

* and ** illustrate indicators 1% and 5% level significance.
detect structural break; therefore, their outcomes can be spurious. For this purpose, the study employs the Maki (2012) co-integration, which is capable of capturing at least five breaks in a co-integration analysis. The Maki co-integration test outcome was reported in Table 6. The outcome reveals that at a 5% significant level, co-integration association among ecological footprints and its regressors, PPI, GDP, REN, and FD, at shift and trend regime over the considered period was evident. This asserts the presence of the co-movement among ecological footprints and its regressors in the presence of a structural break. The present study also used the bound testing approach as a robustness check for the Maki co-integration outcome, which was reported in Table 7. The outcomes disclosed the presence of the co-integration between ecological footprint and its regressors.

Since co-integration is present among the series, the study utilizes the ARDL approach to scrutinize the effects of GDP, REN, PPI, and FD on the ecological footprint in Brazil. Table 7 summarizes the ARDL estimates in the long run for the considered period. As described in Table 6, GDP, REN, PPI, and FD are significant determinants of Brazil’s ecological footprint in both the short and long run. Specifically, we observed that GDP increases ecological footprint, indicating that a 1% increase in economic expansion would increase ecological footprint by 1.33%. Brazil has experienced remarkable economic expansion over the last decades, although this growth has been at the expense of environmental quality. This finding is consistent with the studies of Kirikkaleli et al. (2020), Nathaniel et al. (2021), Hassan et al. (2019), Charfeddine and Mrabet (2017), Wang and Dong (2019), Bello et al. (2018), Destek and Sinha (2020), Ahmed et al. (2020), Alola et al. 2019, and Dogan et al. (2019). A possible reason for this is that like any other emerging economy, Brazil’s need for energy is paramount for it to achieve continuous growth. These energy demands are met using conventional energy sources such as oil, gas, and coal, which account for about 57.68% of the energy consumed in 2017. These fossil fuels are the major contributor to environmental deterioration, and it will be difficult for growth to persist if environmental conditions continue to deteriorate. This does not conform with the principles of SDGs. Another reason is that Brazil is an industrialized economy whose economic development has been accelerated by the exploitation and extraction of natural resources, which has caused a reduction in the environmental biocapacity while increasing the ecological footprint. Thus, policymakers should take into account strategies that include environmental awareness, cultural norms, consumer responsibility, respect for nature, and the realization of the inherent worth of nature and life to help reduce and avoid the consequences of global warming.

Moreover, renewable energy use will reduce the ecological footprint, since the interaction between renewable energy use and ecological footprints is negative and statistically significant. For example, ecological footprint will decrease by 0.46% as renewable energy use increases by 1% in Brazil. This is in agreement with the studies of Wang and Dong (2019), Adebayo and Kirikkaleli (2021), Usman et al. (2021), Murshed et al. (2021), Ulucak and Khan (2020), Destek and Sinha (2020), and Alola et al. (2019) for 14 sub-Saharan African nations, the 15 highest emitting countries, South Asia, BRICS, OECD countries, and EU countries, respectively. This empirical result is encouraging for the goal of reducing harm to the environment in Brazil, with policy implications for other emerging economies. This finding indicates that the use of traditional (conventional) energy resources is the primary source of environmental damage. This also shows that there is an urgent need to shift the economy away from non-renewable energy resources to renewable energy resources. The possible cause for this outcome is Brazil’s pursuit of a clean energy matrix policy with incentives for more low-carbon measures (Pereira et al. 2012); however, about 47% of Brazil’s energy mix is composed of renewable energy sources, with 89% of the electricity supplied from renewable energy resources (IEA, 2020), whereas Brazil is the third-largest user of renewable sources in the world after China and the USA (Pao and Fu 2013). It has intensified the use and development of renewable energy sources through the development of public-private initiatives to alleviate the impact of greenhouse gases on the environment, which is a significant contributor to air pollution. Moreover, contrary to our expectations, public-private partnership investment in energy has an adverse impact on environmental sustainability in Brazil, inferring that a 1% increase in PPI will cause the ecological footprint to increase by 0.019%. A reasonable explanation for this outcome could be the strong connection between PPI and energy sources related to fossil fuels. The studies of Kirikkaleli and Adebayo et al. (2021), Shahbaz et al. (2020), and Khan et al. (2020) are consistent with this outcome.

Furthermore, financial development has an adverse effect on ecological footprint; precisely, an increase in financial development by 1% triggers a reduction in ecological footprint of 0.17%. Similar studies such as Baloch et al. (2019), Naqvi

### Table 5: Unit root without break

| Variables | $T$-statistics | Break-year | $T$-statistics | Break-year |
|-----------|----------------|------------|----------------|------------|
| EF        | $-3.4287$      | 2001       | $-7.2294^*$    | 2010       |
| GDP       | $-3.7732$      | 2010       | $-6.2933^*$    | 2010       |
| REN       | $-2.4331$      | 1991       | $-6.1372^*$    | 2003       |
| PPI       | $-6.1938^*$    | 1997       | $-8.0728^*$    | 2000       |
| FD        | $-3.8038$      | 1994       | $-7.8203^*$    | 2006       |

*illustrates indicator significance at 1% level
et al. (2020), and Destek and Sarkodie (2019) also corroborated this outcome, but Usman et al. (2020a) reported opposite findings. This negative connection affirms that the financial sector in Brazil apportions funds or resources towards improving the quality of the environment, while also supporting institutions, corporations, and industries that use eco-friendly technologies. In addition, a major strategy to attract foreign investment for research and development initiatives is to promote the liberalization and stability of the financial sector, which is key in funding eco-friendly technological innovations that can play a major role in decreasing ecological footprint.

The outcomes of the ARDL short run have also been presented in Table 7. The empirical evidence reveals that economic and public-private partnership investment in energy triggers ecological footprint in Brazil. In addition, renewable energy use and financial development have an adverse effect on ecological footprint. Finally, as expected, the ECM (41%) is negative and statistically significant. Hence, within 1 year, the disequilibrium between ecological footprint and its regressors is corrected, indicating convergence towards the equilibrium in the long run. Diagnostic tests were also carried out, the results of which have been reported in Table 6 and Figures 1 and 2.

The robustness check of the long-run estimate was examined by utilizing the dynamic ordinary least square (DOLS) approach. The outcome DOLS is reported in Table 8. The long-run elasticities for DOLS are seen to corroborate with ARDL estimates in the long run. The DOLS long-run elasticities of GDP, REN, PPI, and FD are 1.33%, −0.12%, 0.02%, and −0.18%, respectively (Table 9).

It is not sufficient to determine whether the chosen variables have a positive or negative relationship; it is, therefore, necessary to determine which variable is influencing or transmitting directly to the other variable. This helps policymakers to formulate policies that are necessary for adjustments. In exposing this flowing (unidirectional or bidirectional) among the considered variable, the Granger causality provides solid ground for this. Since conventional causality test outcome is usually inconsistent because it does not put into consideration the structural break(s) during estimation, this study utilizes the gradual shift causality test to detect the causality between dependent variable, i.e., ecological footprint and its regressors, i.e., GDP, PPI, REN, and FD, as reported in Table 8 The novelty of the gradual shift causality test is that it can capture causal linkage between series in the presence of structural break. We discovered from Table 8 that there is a feedback causal association between GDP and EP, indicating that GDP Granger causes EP and vice-versa in Brazil. This outcome is consistent with Ibrahiem and Hanafy (2020), Danish and Khan (2019), Destek and Sarkodie (2019) for Egypt, Brics economies, 11 newly industrialized economies, respectively. Moreover, there is a unidirectional causal association found from renewable energy to ecological footprint, which implies that renewable energy has predictive control over the ecological footprint within the study period. In addition, we detected a unidirectional causal interaction from ecological footprint to public-private partnership investment in energy, indicating that ecological footprint can significantly predict public-private partnership. This finding is consistent with the study of Shahbaz et al. (2018) for France. Lastly, there is a bidirectional causal association between financial development and ecological footprint, establishing a feedback hypothesis. This outcome is consistent with the findings reported by Chen et al. (2019), Usman and Hammar (2020), and Yao et al. (2021) (Table 10).

Table 6  Maki co-integration test

| Model | T-statistics | Critical values | Break-years |
|-------|-------------|----------------|-------------|
| Trend and regime shifts | | | |
| EP=f(GDP, PPI, FD, REN) | −7.13909* | −6.911 | 1998 |
| EP=f(GDP, PPI, FD, REN) | −8.52593* | −7.638 | 1998, 1991 |
| EP=f(GDP, PPI, FD, REN) | −10.2908* | −8.254 | 1998, 1991, 2006 |
| EP=f(GDP, PPI, FD, REN) | −10.2908* | −8.871 | 1998, 1991, 2006, 2012 |
| EP=f(GDP, PPI, FD, REN) | −10.2908* | −9.482 | 1998, 1991, 2006, 2012, 1995 |

5% significance level is signified by *

Table 7  ARDL bound test

| Model | Optimal lag | F-statistics | Co-integration |
|-------|-------------|--------------|----------------|
| EF = f(GDP, REN, PPI, FD) (2,4,3,4,4) | 24.2468* | Yes |
| Level of significance | L-BO | U-BO |
| 1% | 3.74 | 5.06 |
| 2.5% | 3.25 | 4.49 |
| 5% | 2.86 | 4.01 |
| 10% | 2.45 | 3.52 |

1% level of significance denoted as *, U-BO denotes the upper bound, while L-BO denotes the lower bounds.
Conclusion and policy implication

This research explores the long-term and causal impact of economic growth and renewable energy on ecological footprint by considering the role of public-private partnership investment in energy and financial development for Brazil by utilizing the annual series data between 1984 and 2017. To the best of the authors’ knowledge, no prior studies have investigated this association in the context of Brazil. Both the Maki and ARDL bound testing co-integration techniques were used to explore the long-run co-integration. These co-integration techniques confirm co-integration was evident among renewable energy use, public-private investment in energy, economic growth, and financial development. The outcomes of the ARDL disclosed that GDP and PPI have a positive and significant influence on ecological footprint, while financial development and renewable energy have a negative impact on Brazil’s ecological footprint. This implies that both financial development and renewable energy reduce CO₂ emissions for the Brazilian economy. This implies that both financial development and renewable energy consumption can play a positive and significant role in combating environmental degradation in the country as greater financial sector development can facilitate more financing at lower costs (as the country’s financial institution is dominated by commercial banks, which the main function is to provide loans to both public and private sectors for various developmental projects) including for investment in environmental projects. In such a case, when
future carbon emission demand projection is considered, the importance of financial institutions must be incorporated in addition to the role of conventional factors such as income and energy. Also, an increase in the consumption of green energy can help in mitigating environmental degradation in Brazil. The outcomes of the causality test disclosed a bidirectional causal linkage between GDP and ecological footprint. Also, there is evidence of a one-way causal linkage from public-private investment in energy and renewable energy to ecological footprint in Brazil.

Based on the above conclusions, this paper proposes relevant policy implications as follows: First, at the national level, the government of Brazil should be careful when formulating economic expansion policies that will jeopardize environmental sustainability. Second, the total energy mix should be changed by substituting non-renewable energy sources with renewable energy use since clean energy aids in mitigating environmental degradation in Brazil. Third, improve the carbon trading market for PPP climate finance, and accelerate the research and establishment of a national unified carbon emission permit market system based on existing environmental exchanges across Brazil, guide pilot provinces and cities to establish their own carbon emission permit allocation schemes and trading mechanisms, and establish regional carbon emission trading platforms by cooperating with provincial and municipal economic and information commissions, energy conservation and emission reduction groups, and other functional departments; thus, Brazil’s carbon trading pricing power can be formed as soon as possible to promote the development of low-carbon industry. Moreover, actively promote the research and development of low-carbon technologies, which are the key factors in Brazil’s transition to a low-carbon economy, develop technologies for clean development and utilization of coal energy and for carbon dioxide capture and storage, develop a circular economy, build a circular system for all industries, and vigorously promote the recycling of industrial and household waste.

Fourth, since financial development impacts EF negatively, efforts to curtail emissions of clients that receive funding and other services from the financial sector should be initiated. In doing this, the banking system may give priority or incentives to loan that is related with less emission business endeavors in the form of interest discounts. The financial system

| Table 8 | ARDL outcomes |
|---------|---------------|
| Dependent variable | Analysis | Regressors | Coefficient | T-statistics |
| EP | Long run | GDP | 1.3336 | 9.5918* |
| | | REN | −0.4635 | −5.0711* |
| | | PPI | 0.0196 | 5.8629* |
| | | FD | −0.1786 | −3.4599* |
| EP | Short run | ECM(-) | −0.4117 | −13.4852* |
| | | GDP | 1.3336 | 19.6138* |
| | | REN | −0.1153 | −2.7517** |
| | | PPI | 0.0196 | 10.3117* |
| | | FD | −0.1786 | 8.2036* |

Diagnostic tests
- χ² heteroscedasticity: 0.789 (0.6880)
- χ² Ramsey: 4.313 (0.9949)
- χ² normality: 0.960 (0.6184)
- χ² LM: 2.093 (0.2097)

* and ** denote 1% and 10% significance levels respectively.

Table 9 | Robustness check |
|---------------|------------------|
| Regressors | Coefficient | T-statistic |
| GDP | 1.3336 | 20.0340* |
| REN | −0.1153 | −2.1351** |
| PPI | 0.0196 | 9.0341* |
| FD | −0.1786 | −7.8084* |

* & ** stand for 1% & 5% significance levels
may as well add emission-related conditions to their existing financial product or impute emission-related costs in their financial products. Summarily, in future consideration of environmental quality in Brazil, the role of the financial sector must be accorded credence.

Though the present study utilized ecological footprint as a metric for environmental degradation, the roles of important factors including urbanization, land use, and government spending (especially government subsidy) on emissions are not considered in this research. Furthermore, additional studies should be conducted in different developing and developed nations to investigate these associations.

Availability of data and materials The data that support the findings of this study are available from the World Bank.

Author contribution TSA, DK, and GDA designed the experiment and collected the dataset. The introduction and literature review sections are written by SU, AAA, and IA. DK and GDA constructed the methodology section and empirical outcomes in the study. GDA, TSA, and SU contributed to the interpretation of the outcomes. All the authors read and approved the final manuscript.

Declarations

Ethics approval We confirmed that this manuscript has not been published elsewhere and is not under consideration by another journal. Ethical approval and informed consent are not applicable for this study.

Consent to participate Not applicable.

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Competing interests The authors declare no competing interests.

References

Adebayo TS, Kirikkalei D (2021) Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. Environment Development and Sustainability, pp 1–26

Adebayo TS, Awosusi AA, Kirikkalei D, Akinsola GD, Mwamba MN (2021) Can CO₂ emissions and energy consumption deter the economic performance of South Korea? A time series analysis. Environ Sci Pollut Res:1–16

Ahmed Z, Wang Z, Mahmood F, Hafeez M, Ali N (2019) Does globalization increase the ecological footprint? Empirical evidence from Malaysia. Environ Sci Pollut Res 26(18):18565–18582

Ahmed Z, Asghar MM, Malik MN, Nawaz K (2020) Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. Res Policy 67:101677

Ahmed Z, Zhang B, Cary M (2021) Linking economic globalization, economic growth, financial development, and ecological footprint: evidence from symmetric and asymmetric ARDL. Ecol Indic 121:107060

Alola AA, Bekun FV, Sarkodie SA (2019) Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. Sci Total Environ 685:702–709

Anasri MA, Ahmad MR, Siddique S, Mansoor K (2020) An environment Kuznets curve for ecological footprint: evidence from GCC countries. Carbon Management 11(4):355–368

Awosusi AA, Adebayo TS, Odugbesan JA, Akinsola GD, Wong WK, Rjough H (2021) Sustainability of energy-induced growth nexus in Brazil: do carbon emissions and urbanization matter? Sustainability 13(8):4371

Baloch MA, Zhang J, Iqbal K, Iqbal Z (2019) The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation. Environ Sci Pollut Res 26(6):6199–6208

Bello MO, Solarin SA, Yen YY (2018) The impact of electricity consumption on CO₂ emission, carbon footprint, water footprint and ecological footprint: the role of hydropower in an emerging economy. J Environ Manag 219:218–230

Charfeddine L (2017) The impact of energy consumption and economic development on ecological footprint and CO₂ emissions: evidence from a Markov switching equilibrium correction model. Energy Econ 65:355–374

Charfeddine L, Mrabet Z (2017) The impact of economic development and social-political factors on ecological footprint: a panel data analysis for 15 MENA countries. Renew Sust Energ Rev 76:138–154

Chen S, Saud S, Saleem N, Bari MW (2019) Nexus between financial development, energy consumption, income level, and ecological footprint in CEE countries: do human capital and biocapacity matter? Environ Sci Pollut Res 26(31):31856–31872

Danish UR, Khan SUD (2019) Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustain Cities Soc 54:101996

Destek MA, Sarkodie SA (2019) Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development. Sci Total Environ 650:2483–2489

Destek MA, Sinha A (2020) Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: evidence from Organisation for economic co-operation and development countries. J Clean Prod 242:118537

Destek MA, Ulucak R, Dogan E (2018) Analyzing the environmental Kuznets curve for the EU countries: the role of ecological footprint. Environ Sci Pollut Res 25(29):29387–29396

Dogan E, Taspinar N, Gokmenoglu KK (2019) Determinants of ecological footprint in MINT countries. Energy & Environment 30(6):1065–1086

Engle RF, Granger CW (1987) Co-integration and error correction: representation, estimation, and testing. Econometrica: journal of the Econometric Society 55:251–276

Godil DI, Sharif A, Rafique S, Jamsitiipasert K (2020) The asymmetric effect of tourism, financial development, and globalization on ecological footprint in Turkey. Environ Sci Pollut Res 27(32):40109–40120

Hassan ST, Xia E, Khan NH, Shah SMA (2019) Economic growth, natural resources, and ecological footprints: evidence from Pakistan. Environ Sci Pollut Res 26(3):2929–2938

Ibrahim DM, Hanafy SA (2020) Dynamic linkages amongst ecological footprints, fossil fuel energy consumption and globalization: an empirical analysis. Management of Environmental Quality: An International Journal

Johansen S (1991) Estimation and hypothesis testing of co-integration vectors in Gaussian vector autoregressive models. Econometrica: journal of the Econometric Society 59:1551–1580

Kassouri Y, Altuntas H (2020) Human well-being versus ecological footprint in MENA countries: a trade-off? J Environ Manag 263:110405

Khan Z, Ali M, Kirikkalei D, Wahab S, Jiao Z (2020) The impact of technological innovation and public-private partnership investment on sustainable environment in China: consumption-based carbon emissions analysis. Sustain Dev 28(5):1317–1330
Kirikkaleli D, Adebayo TS (2021) Do public-private partnerships in energy and renewable energy consumption matter for consumption-based carbon dioxide emissions in India? Environ Sci Pollut Res 20:1–14
Kirikkaleli D, Adebayo TS, Khan Z, Ali S (2020) Does globalisation matter for ecological footprint in Turkey? Evidence from dual adjustment approach Environmental Science and Pollution Research 1–9
Langnel Z, Amegavi GB (2020) Globalization, electricity consumption and ecological footprint: an autoregressive distributive lag (ARDL) approach. Sustain Cities Soc 63:102482
Mursheed M, Haseeb M, Alam MS (2021) The Environmental Kuznets Curve hypothesis for carbon and ecological footprints in South Asia: the role of renewable energy. GeoJournal 1–28
Naqvi SAA, Shah SAR, Mehdi MA (2020) Revealing empirical association among ecological footprints, renewable energy consumption, real income, and financial development: a global perspective. Environ Sci Pollut Res 27(34):42830–42849
Nathaniel S, Khan SAR (2021) The nexus between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries. J Clean Prod 272:122709
Nathaniel SP, Mursheed M, Bassim M (2021) The nexus between economic growth, energy use, international trade and ecological footprints: the role of environmental regulations in N11 countries. Energy, Ecology and Environment 1–17
Naziqoglu S, Gormus NA, Soytas U (2016) Oil prices and real estate investment trusts (REITs): gradual-shift causality and volatility transmission analysis. Energy Econ 60:168–175
Pao HT, Fu HC (2013) Renewable energy, non-renewable energy and economic growth in Brazil. Renew Sust Energ Rev 25:381–392
Pata UK, Yilanci V (2020) Financial development, globalization and ecological footprint in G7: further evidence from threshold cointegration and fractional frequency causality tests. Environ Econ Stat 27(4):803–825
Pereira MG, Camacho CF, Freitas MAV, Da Silva NF (2012) The renewable energy market in Brazil: current status and potential. Renew Sust Energ Rev 16(6):3786–3802
Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. J Appl Econ 16(3):289–326
Phillips PC, Perron P (1988) Testing for a unit root in time series regression. Biometrika 75(2):335–346
Ramzan M, Adebayo TS, Iqbal HA, Awosusi AA, Akinsola GD (2021) The environmental sustainability effects of financial development and urbanization in Latin American countries. Environ Sci Pollut Res 1–14
Nathaniel SP, Mursheed M, Bassim M (2021) The nexus between economic growth, energy use, international trade and ecological footprints: the role of environmental regulations in N11 countries. Energy, Ecology and Environment 1–17
Rudolph A, Figge L (2017) Determinants of ecological footprints: what is the role of globalization? Ecol Indic 81:348–361
Sabir S, Gorus MS (2019) The impact of globalization on ecological footprint: empirical evidence from the South Asian countries. Environ Sci Pollut Res 26(32):33387–33398
Said SE, Dickey DA (1984) Testing for unit roots in autoregressive-moving average models of unknown order. Biometrika 71(3):599–607
Saud S, Chen S, Haseeb A (2020) The role of financial development and globalization in the environment: accounting ecological footprint indicators for selected one-belt-one-road initiative countries. J Clean Prod 250:119518
Shahbaz M, Nasir MA, Roubaud D (2018) Environmental degradation in France: the effects of FDI, financial development, and energy innovations. Energy Econ 74:843–857
Shahbaz M, Raghutla C, Song M, Zameer H, Jiao Z (2020) Public-private partnerships investment in energy as new determinant of CO2 emissions: the role of technological innovations in China. Energy Econ 86:104664
Stock JH, Watson MW (1993) A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica: Journal of the Econometric Society 71:783–820
Tufail M, Song L, Adebayo TS, Kirikkaleli D, Khan S (2021) Do fiscal decentralization and natural resources rent curb carbon emissions? Evidence from developed countries. Environ Sci Pollut Res 1–12
Udenna EN (2020) A sustainable study of economic growth and development amidst ecological footprint: new insight from Nigerian perspective. Sci Total Environ 732:139270
Ulucak R, Khan SUD (2020) Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustain Cities Soc 54:101996
Usman M, Hammar N (2020) Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: fresh insights based on the STIRPAT model for Asia Pacific Economic Cooperation countries. Environ Sci Pollut Res 1–18
Usman O, Akadiri SS, Adeshola I (2020a) Role of renewable energy and globalization on ecological footprint in the USA: implications for environmental sustainability. Environ Sci Pollut Res 27:30681–30693
Usman O, Irtorel IB, Ike GN (2020b) Enhancing sustainable electricity consumption in a large ecological reserve–based country: the role of democracy, ecological footprint, economic growth, and globalisation in Brazil. Environ Sci Pollut Res 27(12):13370–13383
Usman M, Mahhdum MSA, Kouasar R (2021) Does financial inclusion, renewable and non-renewable energy utilization accelerate ecological footprints and economic growth? Fresh evidence from 15 highest emitting countries. Sustain Cities Soc 65:102590
Wackernagel M, Rees W (1998) Our ecological footprint: reducing human impact on the earth (Vol. 9). New society publishers
Wang J, Dong K (2019) What drives environmental degradation? Evidence from 14 Sub-Saharan African countries. Sci Total Environ 656:165–173
Wang Z, Bui Q, Zhang B, Pham TTH (2020) Biomass energy production and its impacts on the ecological footprint: an investigation of the G7 countries. Sci Total Environ 743:140741
Wang KH, Liu L, Adebayo TS, Lobon OR, Claudia MN (2021) Fiscal decentralization, political stability and resources curse hypothesis: a case of fiscal decentralized economies. Res Policy 72:102071
Waqih MAU, Bhutto NA, Ghumro NH, Kumar S, Salam MA (2019) Rising environmental degradation and impact of foreign direct investment: an empirical evidence from SAARC region. J Environ Manag 243:472–480
World Bank (2021) World development indicators. http://data.worldbank.org/. Accessed March 2021
Yao X, Yasseen R, Hussain J, Shah WUH (2021) The repercussions of financial development and corruption on energy efficiency and ecological footprint: evidence from BRICS and Next 11 Countries. Energy 120063
Yilanci V, Pata UK (2020) Investigating the EKC hypothesis for China: the role of economic complexity on ecological footprint. Environ Sci Pollut Res 1–12
Zhang L, Li Z, Kirikkaleli D, Adebayo TS, Adeshola I, Akinsola GD (2021) Modeling CO2 emissions in Malaysia: an application of Maki cointegration and wavelet coherence tests. Environ Sci Pollut Res 28(20):26030–26044
Zivot E, Andrews DWK (2002) Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. J Bus Econ Stat 20(1):25–44

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