frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 31 July 2025
DOI 10.3389/fenrg.2025.1490841

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OPEN ACCESS

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RECEIVED 03 September 2024
ACCEPTED 07 July 2025
PUBLISHED 31 July 2025

CITATION
Adeneye YB and Rasheed S (2025) Impact of coal consumption, ecological footprint on economic growth: new evidence from top seventeen coal countries.
Front. Energy Res. 13:1490841.
doi: 10.3389/fenrg.2025.1490841

Impact of coal consumption, ecological footprint on economic growth: new evidence from top seventeen coal countries

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Introduction: This study explores the long-run relationship between coal consumption, ecological footprint, and economic growth in 17 coal-dependent countries from 1980 to 2022. This study further examines how ecological footprint and fossil fuel (Coal consumption) influence economic growth across different economic and ecological contexts.

Methods: The study employs Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators to assess long-run relationships. Additionally, the Three-Stage Least Squares (3SLS) method is used to address potential endogeneity and investigate bidirectional and directional relationships among variables. The sample is further categorized into developed vs. developing countries and ecologically surplus vs. ecologically deficient countries to assess heterogeneity in the findings.

Results: Empirical results reveal significant positive relationships between coal consumption, ecological footprint and economic growth in developing and ecologically deficient countries. However, this empirical finding is insignificant in developed and ecologically surplus countries. Additionally, the 3SLS results uncover a bidirectional negative relationship between coal consumption and economic growth, alongside strong directional positive relationships between coal consumption and ecological footprint, and between ecological footprint and economic growth, both significant at the 1% level. Moreover, the Environmental Kuznets Curve (EKC) hypothesis holds true for developed countries.

Discussion: The findings suggest a strong dependence on coal-driven growth in developing and ecologically deficient nations, highlighting sustainability concerns. Policymakers are urged to initiate a gradual shift from fossil fuels, particularly coal, to renewable energy sources. Recommendations include the promotion of public-private partnerships in energy innovation, the implementation of regulatory frameworks for fossil fuel consumption, and the provision of financial incentives for renewable energy adoption. These measures are essential for aligning economic growth with environmental sustainability across diverse economic and ecological landscapes.

KEYWORDS

ecological footprint, coal consumption, economic growth, coal countries, ecological surplus countries, ecological deficit countries

1 Introduction

In recent times, environmental sustainability has emerged as one of the most demanding concerns of the 21st century, due to continuous expansion of global economic activities (Ibrahim et al., 2023; Wang et al., 2022). However, rapid economic development and reliance on non-renewable energy sources have led to significant environmental concerns, including climate change, biodiversity loss, and greenhouse gas emissions (Awosusi et al., 2023; Destek and Aslan., 2017). Recognizing the urgency of transition to cleaner energy sources, reduce carbon footprints, and achieve sustainable development goals, nations worldwide have come together under critical international agreements, for example, Kyoto Protocol 1997, followed by the landmark Paris Agreement 2015, aims to keep the global average temperature well below 2°C above pre-industrial levels, with efforts directed at limiting the increase to 1.5°C (Alper et al., 2022; Awosusi et al., 2023; Jie et al., 2023). Additionally, the annual Conferences of the Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC) have provided a platform for countries to negotiate and collaborate on climate strategies, the recent conference COP28 held in Dubai, signalled a significant milestone in transition away from fossil fuels, highlighted the need for a swift, equitable, and equitable transition, supported by substantial emissions reductions and enhanced financial mechanisms, ensuring to maintain the global temperature within the 1.5° threshold.

In the era of climate change, coal stands out as the most cost-effective and abundant fossil fuel globally, catalysing global development, electricity generation and poverty alleviation (Kanat et al., 2022). In emerging economies, coal remains a significant energy resource, fuelling rapid industrial expansion and urbanization, primarily due to its substantial reserves, lower prices, affordability, and reliability in providing consistent energy (Chang et al., 2017). These factors have positioned coal as a preferred fossil energy source for many countries seeking to meet their energy demand (Al-mulali & CheSab, 2018). In contrast, developed nations towards shifting towards cleaner energy alternatives, have make it a cornerstone for energy security through coal efficiency (Awosusi et al., 2024), action to cut methane emissions from coal mines and carbon capture storage (CCS) technologies (Li, 2023a; Li, 2023b). However, coal contributes to severe environmental challenges through greenhouse gas emissions, exacerbating climate change. Coal accounts for approximately 15.5 GH of global carbon emissions due to increase in global coal-fired power generation by 2%, leading to record-high CO_2 emissions from coal-fired plants (International Energy Agency 2022). Consequently, the combustion of fossil fuels, especially in the form of coal, has resulted in significant environmental degradation and deterioration, posing an urgent climate challenge and negative health effects on humans (Li et al., 2022), ultimately resulting in higher healthcare costs (Chang et al., 2017). Moreover, as economies grow and industries flourish, the demand for coal energy, natural resources, and land increases, thereby decreases the environment quality (Hassan et al., 2019; Kim and Yoo., 2016; Tauseef et al., 2019).

The ecological footprint, as a critical measure for assessing the environmental impact of human activities on the planet (both productive land and sea areas used for consumption and production) (Wackernagel and Rees, 1998), thus provides a holistic approach on the pressure humans exert on the planet. The ecological footprint offers a comprehensive measure of environmental sustainability than traditional measure, i.e., carbon emission, by integrating various dimensions of human impact, such as carbon emissions, resource consumption, and land use (Wang et al., 2022). The rapid increase in domestic and industrial production, resource utilization, and energy consumption in developing countries has accelerated ecological footprints (Wang et al., 2022). As a result, energy consumption, vital for economic growth intensifies resource exploitation, leading to higher fossil fuel use and CO_2 emissions, thus reduces the environmental quality (Majeed et al., 2021). This paradox of economic dependence on coal and the need for ecological sustainability has stimulated a critical discourse on the trade-offs between coal consumption, ecological footprints, and economic growth, in order to design and implement robust policies that facilitate the transition from fossil fuels and promote long-term environmental sustainability.

Against this backdrop, this paper primarily aims to evaluate the impact of coal consumption and ecological footprint on economic growth in the top 17 coal consumption countries. Previous studies (e.g., Danish et al., 2018; Kongkuah et al., 2021) have used the conventional proxy for environmental degradation, i.e., carbon dioxide (CO_2) emissions. However, CO_2 does not encompass the multi-dimensional aspects of environmental quality (Altıntaş and Kassouri, 2020; Dogan et al., 2020). Therefore, this paper uses the ecological footprint (EF) as a proxy for environmental quality, introduced by Wackernagel and Rees (1998) to address the limitations of CO_2 emissions. The ecological footprint (EF) measures the environmental adversities concerning bio-productive land area, which is used by humans for their diversified desires and adjusts the wastes generated by humans in the process (Rees, 2000). We employed the Fully Modified OLS, Dynamic OLS, and three-stage least squares (3SLS) to achieve the study's objectives.

The contributions of the study are fourfold. Our study is among the recent studies that established an asymmetric relationship between environment and growth, which supports the conditional

Abbreviations: COAL, Coal consumption; GDP, Economic growth; GDPsquare, Square of economic growth; EF, Ecological footprint; POP, Population; TRADEOPEN, Trade openness; FDI, Foreign Direct Investment; 3SLS, Three-stage least squares; ARDL, Autoregressive distributed lag; DOLS, Dynamic OLS; FMOLS, Fully Modified OLS; ADF, Augmented Dickey-Fuller.

EKC hypothesis. Our findings reveal that the relationships between coal consumption, ecological footprint, and economic growth across coal countries vary significantly depending on their levels of development and ecological stratifications. We find that coal and ecological footprint significantly promote economic growth in developing and ecologically deficit countries, while developed and ecologically surplus countries experience significant negative impacts. This suggests new insights in energy literature that the turning point of the EKC hypothesis differs following a country's income level and resource capacity. Methodologically, our paper integrates ecological surplus and deficit classifications into the analysis of energy-growth-environment dynamics by offering a more sustainability-aligned framework, beyond the traditional standard GDP-based classifications. Thus, our findings encourage the need for localized policy insights.

Second, our study contributes to the growth hypothesis, particularly in ecologically deficient countries where coal consumption and ecological footprint drive growth. Unlike most prior studies (Apergis and Payne, 2010; Jia et al., 2022; Jim and Kim, 2018), our findings establish that despite global energy transition discourse and policy narratives, coal consumption remains a significant growth determinant for lower-income or developing economies. Similarly, we find strong support for the EKC hypothesis across developmental stages, with GDP and GDP square having both positive and negative effects on coal consumption, respectively. Therefore, our findings add theoretical robustness to the integration of growth and EKC hypotheses. Third, in contrast to studies that assume the energy-growth relationship as unidirectional causality, we treat the coal-growth models as jointly determined systems using three-stage least squares (3SLS), which account for endogeneity, simultaneous causality, and feedback effects. For instance, coal consumption and ecological footprint significantly impact GDP, while GDP and ecological footprint significantly impact coal consumption, which reinforces the presence of two-way causality.

Third, unlike previous studies (Chang et al., 2017; Salahuddin et al., 2018) that have relied on Granger causality tests to understand the causal relationship between variables despite it being an insufficient measure of economic causality (Malik, 2021), we employ the simultaneous equation modelling approach using the three stages least square (3SLS) proposed by Zellner (1992). This approach allows for interdependence between regressors and regressand (Malik, 2021), and provides consistent, reliable and unbiased results by solving the correlation between unobserved error and regression terms (Ren et al., 2021). This paper incorporates relevant explanatory variables in every equation of 3SLS to overcome the problem of omitted variable bias. Unlike past studies that used Granger causality to find a unidirectional relationship between coal and economic growth and support for the neutrality and feedback hypotheses (Chang et al., 2017; Lin et al., 2018), our study in the use of the 3SLS finds a bidirectional negative relationship between coal consumption and economic growth. Also, we find directional positive relationships between coal consumption and ecological footprint and between ecological footprint and economic growth at the 1% level. Our findings of the ecological footprint model using 3SLS confirm the EKC hypothesis in developed countries while it is not confirmed in developing and ecological surplus countries, suggesting that environmental quality starts to improve at the same time as economic growth (Pata, 2018), due to increasing level of environmental awareness, stringent environmental regulations and the transition to low-carbon production technologies (Anoruo, 2017).

Lastly, by conducting sub-sample analysis, this study provides insights into the divergent effects of different ecological typologies (i.e., ecological deficit and ecological surplus) on economic growth by analysing data from the global ecological footprint. Countries with ecological surpluses may enjoy favourable economic growth as a result of sustainable resource management, whereas ecological deficit countries are confronted by the challenges and possible risks of resource depletion and environmental degradation. Our findings show that in ecological deficit countries, both coal consumption and ecological footprint have a positive and significant impact on economic growth. Conversely, in ecological surplus countries, coal consumption exerts a positive but insignificant influence on economic growth, while ecological footprint exhibits a positive and significant impact on economic growth. This subsample analysis provides policymakers and stakeholders with insights for formulating sustainable development strategies, fostering responsible environmental behaviour, as well as achieving an equilibrium approach to growth in the economy that incorporates ecological considerations into account.

The remainder of the paper is organised as follows. The literature review section provides a related literature review. The "Data and Methodology" section offers the data and econometric methodology. The "Empirical Results section present the empirical results. The last section provides "Discussion and Conclusion.

1.1 Theoretical background

The Energy-Growth nexus is a fundamental theory used to explores the dynamic relationship between energy consumption and economic growth,highlighting four key hypotheses: (1) Growth Hypothesis (EC→GDP),where energy consumption drives economic growth; (2) Conservation Hypothesis (GDP →EC),where economic growth reduces energy consumption through efficiency: (3) Feedback Hypothesis (EC↔GDP),suggesting mutual reinforcement between energy consumption and growth; and (4) Neutrality Hypothesis (EC ⊥ GDP),indicating no relationship between energy consumption and economic growth (Chang et al., 2017; Destek, 2016; Jia et al., 2022; Rahman and Velayutham, 2020).

Moreover, the Environmental Kuznets Curve (EKC) hypothesis is a widely recognized framework for examining the relationship between economic development and environmental quality, developed by Grossman et al. (1991) and coined by Panayotou (1993). This hypothesis assumes that environmental degradation tends to increase during the early stages of economic growth due to factors such as a lack of environmental awareness, inadequate funds allocated for environmental protection, and a scarcity of advanced pollution-preventing technologies. However, as economic development reaches to a mature point, the hypothesis suggests that economic growth can lead to a reduction in environmental degradation, through the adoption of cleaner technologies, increased environmental awareness, shifts in industrial sector towards greener sectors and environmental sustainability (Li and Li., 2011; Wang et al., 2022).

1.2 Empirical literature

The literature extensively investigates the relationship between coal consumption, ecological impact, and economic growth. In summary, we divide the available literature into two major strands: first, we investigate the relationship between coal energy use and economic growth; second, we investigate the relationship between economic growth and ecological footprint.

1.2.1 Coal consumption and economic growth

There is widespread agreement that increasing the consumption of fossil energy sources increases economic growth. As per the British Petroleum report in 2012, coal reserves are dominant contributors to the global energy mix. As a result, coal has become one of the world's primary and critical energy sources (Kanat et al., 2022). Numerous noteworthy research has been carried out over time to thoroughly study the distinct relationship between coal consumption and economic growth. For example, Nasiru (2019) confirms the long-run relationship between coal consumption and economic growth in Nigeria. Further, the conservation hypothesis was confirmed between coal consumption and economic growth. In another study, Jin and Kim (2018) support the growth hypothesis between coal consumption and economic growth in 32 non-OECD countries, from 1990–2013. Further, Al-mulali and Che Sab (2018) confirm the neutrality hypothesis in the top ten coal-consuming countries from 1992 to 2009. Similarly, in BRICS, Chang et al. (2017) evidenced the growth hypothesis for China, the feedback hypothesis for India, the conservation hypothesis for South Africa and the neutrality hypothesis for Brazil and Russia.

1.2.2 Cological footprint and economic growth

This section highlights the relationship between environmental degradation-economic growth. The relationship between environment and economic growth was largely based on EKC in various countries and regions using carbon emission as an indicator of environmental pollution, for example, Al-mulali et al. (2015) confirm the EKC hypothesis in 93 countries, Shahbaz et al. (2019) confirmed in G-7 countries, Wang et al. (2022) confirmed in China, Danish et al. (2018) and Rahman and Ahmad (2019) validated in Pakistan. However, some studies do not support the EKC hypothesis in 31 Asian countries (Aye and Edoja, 2017), the EU (Dogan et al., 2020), and China (Kongkuah et al., 2021).

In recent years ecological footprint has emerged as a new indicator of environmental degradation, surpassing the sole focus on carbon dioxide emissions. It provides a more comprehensive and quantitative measurement of sustainable development by evaluating the extent to which human activities have an impact on the environment (Ashir et al., 2017). Several studies have used ecological footprint as an indicator of environmental degradation, for example, Tauseef et al. (2019) found that economic growth increases the ecological footprint in Pakistan in both the long and short run. Some studies also confirmed the EKC for economic growth and ecological footprint. Similarly, Ulucak and Bilgili (2018) confirmed an inverted U relationship between economic growth and ecological footprint in middle and high-income countries. The authors confirm increases in economic growth increase the ecological footprint up to a certain limit and decrease later. Also, Charfeddine and Mrabet (2017) confirm the EKC in 15 MENA countries. Nathaniel and Nathaniel (2020) confirmed EKC between economic growth and ecological footprint in N-11 countries. In addition, the ecologically induced EKC was also confirmed between economic growth and ecological footprint in West Asian and Middle east countries (Kihombo et al., 2022). Also, Chaudhry et al., (2022) confirmed the presence of the EKC hypothesis between financial inclusion and ecological footprint. Hence, results from an EKC analysis are highly sensitive to the selection of independent variables included in the analysis. Therefore, it is crucial to consider suitable macroeconomic variables that may affect the connection between economic growth and ecological footprint (Dogan and Inglesi-Lotz, 2020).

Prior studies (see Adebayo et al., 2021b; Adebayo et al., 2023; Ding et al., 2023) have investigated the relationship between coal consumption on environment degradation across regions, and nations. However, to the best of our knowledge, there has not been any research that have investigated the combined impact of coal consumption and ecological footprint on economic growth in top coal consuming countries, where coal constitutes a significant portion of fossil fuel consumption and environmental degradation. Additionally, most research generalizes findings across regions or on major economies, neglecting inconsistencies in energy consumption patterns and environmental degradation status. By limiting the focus to the top seventeen coal-consuming countries, this study provides an understanding of the relationship between coal consumption, ecological degradation, and economic growth in these coal-centric contexts. Moreover, previous studies predominantly rely on carbon emissions to measure environmental quality, overlooking a more comprehensive measure of environmental quality, i.e., ecological footprint, which provides a more holistic assessment of environmental quality by accounting for various dimensions of human impact on natural ecosystems. Furthermore, studies have employed traditional econometric approaches like the Granger causality method. In contrast, this study employs a three-stage least squares (3SLS) methodology, which accounts for endogeneity and simultaneous equations, providing more robust and reliable results. In addition, from the review of previous studies, heterogeneity among countries in terms of development status or ecological conditions is rarely accounted for. This research bridges this gap by conducting sub-sample analyses of developing and developed countries, as well as ecological deficit and ecological surplus countries, which enables a deeper understanding of the relationship between the coal consumption-environment-growth nexus.

2 Data and methods

The present study uses annual data on the gross domestic product (US dollar) as a measure of economic growth sourced from World Bank Development Indicators (WDI). Coal consumption (Exajoules) is sourced from the British Petroleum statistical review of world energy. The ecological footprint is measured in global hectares (per capita) from the Global Footprint Network as used in past studies (Ahmed et al., 2020; Al-mulali and Che Sab, 2018; Bildirici and Bakirtas, 2014). The period from 1980 to 2022 was selected due to the availability of consistent data on coal consumption, ecological footprint, and economic growth for the selected sample and post-2015 data exhibit inconsistencies, making it less reliable for analysis. Further, the pre-2015 period is essential for understanding coal consumption trends, particularly in coal-dependent nations, highlighting its impact on economic growth and environmental degradation. This era includes key international agreements like the Kyoto Protocol, which had limited success in reducing coal use. Analysing this period offers an understanding into the effectiveness of early climate policies and provides a baseline for evaluating the environmental cost of coal consumption, crucial for assessing the potential success of post-2015 initiatives such as the Paris Agreement, COP meetings. Additionally, the selection of top seventeen coal consuming countries (Australia, Denmark, Germany, Japan, New Zealand, South Korea, Sweden, the United Kingdom, and the United States, Brazil, China, India, Indonesia, Malaysia, South Africa, Thailand, and Turkey) are taken into consideration, primarily on the highest coal consumers based on world meters database and International energy agency (IEA, 2021). Further, as per report of the IEA (2024), global coal demand reached a record 8,687 Mt, a 2.5% year-over-year increase, driven by countries like China, Australia, India, and the United States, which rely heavily on coal for industrial and economic growth. Despite being major coal consumers and contributors to carbon emissions, these countries are active participants in global climate initiatives, such as the Paris Agreement (2015), highlighting a paradox between their commitments to climate action and continued coal dependency. This study explores the complexities of this duality, seeking to uncover how these countries are making economic development at the cost of environmental degradation. As a general norm, we sourced data on some control variables including financial development, energy consumption, population, urbanisation, foreign direct investment, and trade openness from the World Bank Development Indicators (WDI) database. The inclusion of control variables is to avoid omitted variable bias and to provide more accurate estimates of the parameters in the model specification.

The description of the variables is presented in Table 1. In most of the growth and environmental nexus research, CO_2 emissions are used as an indicator of environmental degradation (Al-Mulali et al., 2015). However, we provided a more reliable and preferred indicator of environmental degradation by using ecological footprint as suggested in environmental policy literature (Ahmed et al., 2019; Ulucak and Bilgili, 2018). In contrast to CO_2 emissions as a measure of environmental degradation, ecological footprint measures the overall consequence of anthropogenic activities, i.e., grazing of land, ocean, croplands, forest products, infrastructure and carbon footprint on the ecosystem (Ahmed et al., 2019; Charfeddine and Mrabet, 2017).

To investigate the long-run relationship between coal consumption, ecological footprint, and economic growth in the top coal-consuming countries, this study employs both Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) methods to ensure robust and reliable estimation results. Firstly, Hardi Z-stat, Phillips-Perron test and ADF- Fisher unit root tests are applied to examine the stationarity properties of the data and followed by Kao (1999), Pedroni (1999) and Westerlund (2007) co-integration test to determine the existence of a long-run equilibrium relationship among the variables. Further, to estimate the long-run impacts of the determinants on each variable, the study employed both Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) techniques. Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) are employed to estimate the long-run relationship among the co-integrating variables and eliminates the presence of endogeneity and serial correlation (Khan et al., 2019). FMOLS developed by Phillips and Hansen (1990) corrects endogeneity and serial correlation non-parametrically by adjusting the OLS estimator. DOLS developed by Stock and Watson (1993), on the other hand, is a parametric approach used to provide optimal estimates of co-integrating regression and addresses endogeneity and serial correlation by including leads and lags of the first differences of the independent variables. Both FMOLS and DOLS solve the problem of endogeneity and eliminate small sample bias (Hardi et al., 2023), thus ensures more accurate and robust estimation of the co-integrating vectors (Fatima et al., 2024). The empirical model representing the long-run relationships among these interconnections as variables is given in Equation 1 as follows:

$$lnGDP_{it} = a_0 + a_1 lnCoal_{it} + a_2 lnEF_{it} + a_3 ln\, FD_{it} + a_4 ln\, Pop_{it} + a_5 lnTradeopen_{it} + u_{it\ldots} \quad (1)$$

Where i represents the number of cross-sectional (example 1,2,3,4 ………………N) and t denotes the period (1980–2022). lnGDP represents economic growth, a_0 represents the slope intercept; $a_1, a_2, a_{3,} a_4 a_5$ represents the coefficients estimated for Coal, ecological footprint, financial development, population, and trade openness. While, u_{it} denotes the error correction term. In addition to the FMOLS estimator, we employed the three-stage equation model (3SLS). The 3SLS estimates not only are robust and asymptotically normal than single equation estimation but allows correlation among unobserved error term across different equations (Bakhsh et al., 2017). The 3SLS provides an alternative to Granger causality that has the limitation of insufficient prediction of economic causality (Malik, 2021). The Equations 2–4 for the 3SLS are presented below:

Growth equation:

$$lnGDP_{it} = a_0 + a_1 lnCoal_{it} + a_2 lnEF_{it} + a_3 ln\, Pop_{it} + a_4 lnTradeopen_{it} + u_{it\ldots} \quad (2)$$

Coal consumption equation:

$$lnCoal_{it} = b_0 + b_1 lnGDP_{it} + b_2 lnEF_{it} + b_3 lnPop_{it} + b_4 lnTradeopen_{it} + \delta_{it\ldots} \quad (3)$$

Ecological footprint equation:

$$ln\, EF_{it} = c_0 + c_1 ln\, GDP_{it} + c_2 lnGDPsquare_{it} + c_3 lnCoal_{it} + c_4 ln\, Urbanisation_{it} + c_5 lnFDI_{it} + \theta_{it\ldots} \quad (4)$$

where, a, b, and c are the coefficients used for regression representing the explanatory variables in the three-stage least square (3SLS) model. “i” represents the countries, and “t” is the year vector and $u_{it}, \delta_{it}, \theta_{it}$ are disturbance terms.

For further analysis encouraged by Ren et al. (2021), we separate our whole panel of 17 countries into developing (Brazil, China, India, Indonesia, Malaysia, South Africa, Thailand, and Turkey) and developed countries (Australia, Denmark, Germany, Japan, New Zealand, South Korea, Sweden, the United Kingdom, and the United

TABLE 1 Variable description.

Variable	Definition	Unit	Source
GDP	GDP per capita	Dollar	World Development Indicator
Ecological footprint	Ecological footprint	Global hectares per capita	Global Footprint Network
Coal	Coal consumption	Exajoules	BP Statistical Review
Financial Development	Domestic credit to the private sector	(% of GDP)	World Development Indicator
FDI	Foreign direct investment	(% of GDP)	World Development Indicator
Urbanisation	Urban population	Total	World Development Indicator
Population	Total population	Total	World Development Indicator
Trade Openness	Imports plus Exports	Doller	World Development Indicator

TABLE 2 Division of countries by economic development and Ecological deficit and surplus.

Group	Countries
Developed Countries	Australia, Denmark, Germany, Japan, New Zealand, South Korea, Sweden, the United Kingdom, and the United States
Developing Countries	Brazil, China, India, Indonesia, Malaysia, South Africa, Thailand, and Turkey
Ecologically Deficient Countries	China, Denmark, Germany, India, Indonesia, Japan, Malaysia, South Africa, South Korea, Thailand, Turkey, the United Kingdom, and the US.
Ecologically Surplus Countries	Australia, Brazil, New Zealand, and Sweden

States) as shown in Table 2 and reconfirm the DOLS and FMOLS and 3SLS estimation process in between developed and developing counties. Also, the full sample was grouped into ecologically deficit CC and ecologically surplus CC as depicted in Table 2.

3 Empirical results

This study investigated the impact of ecological foot and coal consumption on economic growth, using a panel of the top seventeen coal consumption countries. The tests and results are discoursed as follows.

3.1 Descriptive analysis

Table 3 displays the results for the descriptive statistics of variables of the top seventeen coal-consuming countries from 1980–2022. The mean values for all variables are positive. The average values of GDP and GDP-square are 11.719 and 29.90, respectively. Likewise, the mean values of coal and ecological footprint are 1.077 and 1.317, respectively. Similarly, the average values of financial development, FDI, and population are 4.388, 0.737, and 17.983, respectively. Furthermore, the minimum value of 2.815, 5.589, 15.002 and maximum value of 5.300, 2.970, 21.062, with a deviation from mean of 0.647, 1.206, and 1.581 respectively.

TABLE 3 Descriptive Statistics of the full sample.

Variables	Mean	Std. Dev	Min	Max
GDP	11.719	2.315	8.605	17.428
GDPsquare	29.900	19.898	34.698	1.481
Ecological footprint	1.317	0.688	−0.448	2.345
Coal	1.077	2.124	−3.026	6.135
Financial development	4.388	0.647	2.815	5.300
Urbanization	17.522	1.398	14.828	20.456
FDI	0.737	1.206	−5.589	2.970
Trade openness	26.448	1.284	23.828	29.284
Population	17.983	1.581	15.002	21.062

Also, the mean value of urbanisation and trade openness are 17.522 and 26.448 respectively with standard deviation scores of 1.398 and 1.284.

Figures 1–4 also compare (i) ecological-surplus vs. ecological-deficit countries and (ii) developed vs. developing economies

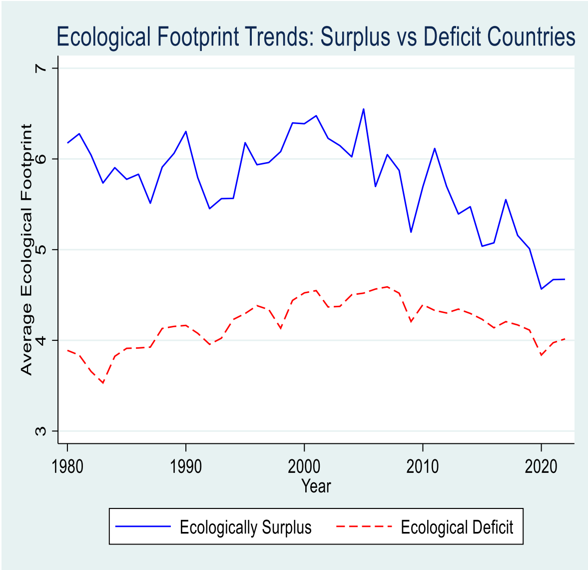

FIGURE 1
EF (Surplus vs. Deficit Countries).

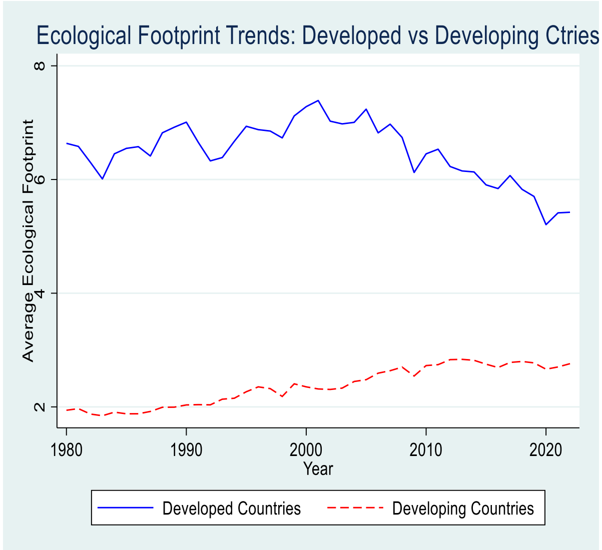

FIGURE 2
EF (Developing vs. Developed Countries).

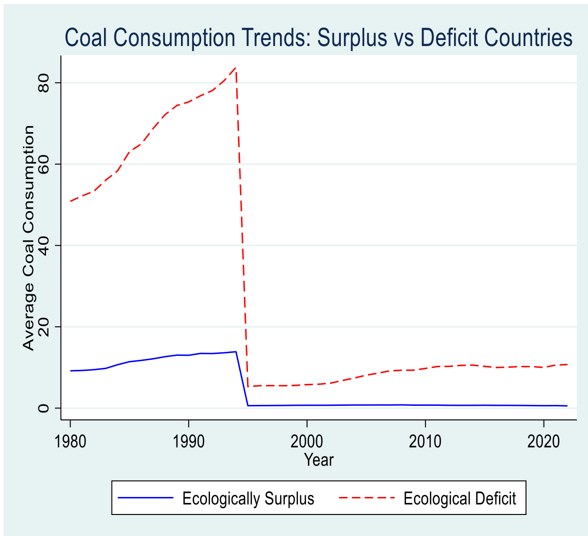

FIGURE 3
CC (Surplus vs. Deficit Countries).

for ecological footprint and coal consumption. As shown in Figure 1, ecological-deficit countries exhibit persistently high and rising ecological footprints, far above their biocapacity limits. In contrast, ecological-surplus countries maintain relatively lower and more stable footprints throughout the sample period. The observed divergence signals rising ecological pressure within deficit nations, thereby demanding the formulation of strategic policy responses aimed at restoring environmental balance. Figure 2 depicts that developed countries consistently exhibit significantly higher ecological footprints, peaking around the early 2000s before showing a gradual decline. In contrast, developing countries maintain much lower footprints throughout the period, with a slow but steady upward trend. This widening gap suggests that while developed countries are beginning to reduce ecological pressure, possibly due to environmental regulations and cleaner technologies. Conversely, the environmental burden in developing economies is intensifying, reflecting the ecological costs associated with rapid industrialization and growth. Figure 3 shows that ecological-deficit countries tend to be more coal-dependent than ecological-surplus countries, reflecting a heavier reliance on carbon-intensive energy systems. The upward trend in coal use in ecological-deficit countries highlights their biocapacity overshoot and emphasizes the need to shift toward cleaner energy sources to ensure environmental sustainability. Lastly, Figure 4 depicts consumption trend varies significantly by development level. It discloses that developed countries, such as the United States and the United Kingdom, have generally reduced their coal use since the mid-2010s likely due to stricter environmental regulations, energy transitions, and technological innovation. Conversely, developing countries like India and China exhibit a consistent rise in coal consumption, reflecting growing energy demand tied to industrialization and economic expansion.

3.2 Comparison of descriptive statistics for ecologically surplus and ecologically deficit countries

Tables 4 and 5 display the results for the descriptive statistics of variables in ecological surplus and deficit countries from 1980 to 2022. The descriptive statistics of ecological surplus and ecological deficit countries differ across different indicators. Ecological surplus countries have a lower GDP mean (11.083) than ecological deficit countries (11.915). However, ecological surplus countries have

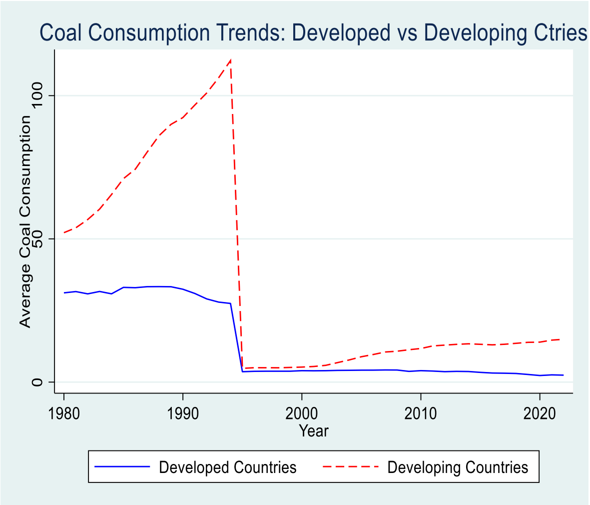

FIGURE 4
CC (Developing vs. Developed Countries).

TABLE 4 Descriptive statistics of ecologically surplus countries.

Variables	Mean	Std. Dev	Min	Max
GDP	11.083	1.113	9.467	13.045
GDPsquare	29.619	0.107	29.352	29.700
Ecological footprint	1.680	0.395	0.917	2.175
Coal	−0.213	1.963	−3.026	3.695
Financial development	4.255	0.580	2.996	5.074
Urbanization	16.558	1.384	14.828	19.031
FDI	1.075	0.951	−1.927	2.970
Trade openness	25.864	0.887	23.828	27.219
Population	16.737	1.410	15.002	19.164

a lower GDP standard deviation (1.113) than ecological deficit countries (2.543), indicating less GDP dispersion. Also, in ecological deficit countries average value for ecological footprint is (1.205) and in surplus countries the average value for ecological footprint is (1.680). Further, the mean value for coal in ecological deficit countries consume is (1.474) and in ecological surplus countries mean value is (−0.213). Regarding financial development, it is (4.255) in ecological surplus countries and in ecological deficit countries the mean value is (4.428).

Concerning urbanisation, ecological surplus countries have mean value of (16.558) than ecological deficit countries have (17.819). In addition, ecological surplus countries have a average (1.075) in foreign direct investment (FDI) and in ecological deficit countries average value is (0.633). Moreover, trade openness has average value of (25.864) in ecological surplus countries and

TABLE 5 Descriptive statistics of ecologically deficient countries.

Variables	Mean	Std. Dev	Min	Max
GDP	11.915	2.543	8.605	17.428
GDPsquare	29.987	1.683	19.898	34.698
Ecological footprint	1.205	0.720	−0.448	2.345
Coal	1.474	2.012	−3.026	6.135
Financial development	4.428	0.661	2.815	5.300
Urbanization	17.819	1.263	15.272	20.456
FDI	0.633	1.257	−5.589	2.970
Trade openness	26.627	1.334	23.828	29.284
Population	18.366	1.427	15.447	21.062

(26.627) in ecological deficit countries. Finally, ecological surplus countries have a greater mean population (18.831) than ecological deficit countries (17.596). In conclusion, descriptive statistics show that ecological surplus and deficit countries differ across metrics and reflects different economic and environmental profiles for the two groups.

3.3 Panel unit root test

To assess the stationarity of the data, panel unit root tests are performed. The results of the unit root tests for Hardi Z-stat, Phillips-Perron test and ADF- Fisher are depicted in Table 6. The Phillips-Perron and ADF-Fisher tests reject the null hypothesis of non-stationary for some variables both at levels I (0) and the first difference I (1), Furthermore, the results of Hardi Z-stat represent that the null hypothesis of non-stationary for all panel variables can be rejected at levels I (0) and for some variables at first difference I (1), whereas, Breitung t-stat shows the null hypothesis of non-stationary for all variables cannot be rejected at levels I (0) but rejected at the first difference I (1).

3.4 Panel cointegration tests

Table 7 provides the results of the Kao (1999), Pedroni (1999) and Westerlund (2007) panel cointegration test. These tests are based on different assumptions and techniques. The Koa test assumes homogeneity in the panel. It follows the background of ADF for the computation of t-statistics. In testing the long-run relationship in a heterogeneous panel, the Pedroni test suggests seven test statistics. These test statistics are classified as "between dimensions" and "within dimensions." The hypotheses of the panel statistic assume that the lagged autoregressive residual across individual units is identical but non-identical in the group statistic. Meanwhile, several authors including Westerlund (2007) have pointed out that Peadroni's statistics are inconsistent and unreliable

TABLE 6 Unit root results.

	Breitung t-stat		Hardi Z-stat		Phillips-Perron test		ADF-Fisher	
	Level	First Diff	Level	First Diff	Level	First Diff	Level	First Diff
GDP	8.7971	−7.3896[a]	93.7436[a]	−0.7145	−1.3461	77.9970[a]	−1.2358	29.0442[a]
	(1.0000)	(0.0000)	(0.0000)	(0.7625)	(0.9109)	(0.0000)	-(0.8917)	(0.0000)
GDPsqr	9.5282	−6.2731[a]	68.81[a]	0.4462	−0.7853	50.221[a]	−2.0895	15.226[a]
	(1.0000)	(0.0000)	(0.0000)	-(0.3277)	(0.7839)	(0.0000)	(0.9817)	(0.0000)
Coal	0.5413	−4.7817[a]	10.1178[a]	4.8312[a]	5.6807[a]	62.3526[a]	4.4136***	35.7080[a]
	-(0.7059)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ecological footprint	5.8371	−8.3924[a]	88.0090[a]	−2.7949	0.8079	95.3662[a]	−1.7928	39.6213[a]
	-(1.0000)	(0.0000)	(0.0000)	-(0.9974)	-(0.2096)	(0.0000)	-(0.9635)	(0.0000)
Financial Dev	1.6186	−8.6155[a]	16.8108[a]	4.3703	−0.2959	37.1183[a]	−0.22	16.2748[a]
	-(0.9472)	(0.0000)	(0.0000)	(0.0000)	-(0.6163)	(0.0000)	-(0.5871)	(0.0000)
FDI	1.1776	−6.4569[a]	60.2511[a]	−3.3919	6.6321[a]	102.2062	1.6649[b]	49.4412[a]
	-(0.8805)	(0.0000)	(0.0000)	-(0.9997)	(0.0000)	(0.0000)	-(0.0480)	(0.0000)
Trade Open	6.5669	−8.3825[a]	91.2706[a]	−2.7929	−2.9295	51.5303[a]	−2.6322	26.0505[a]
	-(1.0000)	(0.0000)	(0.0000)	-(0.9974)	-(0.9983)	(0.0000)	-(0.9958)	(0.0000)
Urbanization	6.6513	−2.4711[a]	92.6563[a]	6.9677[a]	20.8058[a]	83.4933[a]	15.8227[a]	32.5981[a]
	-(1.0000)	-(0.0067)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Population	9.0141	−7.0992[a]	93.2210[a]	−1.7742	−1.2547	102.510[a]	1.4489[c]	60.1511[a]
	-(1.0000)	(0.0000)	(0.0000)	-(0.9620)	-(0.8952)	(0.0000)	-(0.0737)	(0.0000)

Significance level.
[a]1%.
[b]5%.
[c]10%.

in the presence of cross-sectional dependence. Thus, Westerlund and Edgerton (2007) proposed the use of the bootstrap panel cointegration test in calculating the critical values for p-values. Considering the Kao (1999), Pedroni (1999) and Westerlund (2007) test statistics, the null hypothesis, i.e., no cointegration was rejected at the different significance levels as publicized in Table 7. Thus, offers a rich indication of a co-integrating relationship among the variables.

3.5 DOLS and FMOLS results

The results of the FMOLS and DOLS estimators are presented in Table 8. Coal consumption has a significant positive impact on GDP, with coefficients of 0.02 (FMOLS) and 0.01 (DOLS), indicating that higher coal usage is associated with higher economic growth. Similarly, the ecological footprint reveals a positive effect on GDP. These results suggest that higher coal consumption and environmental pressure contribute to the level of economic activities. More so, the results of the control variables showed thattrade openness and DCPS have positive effects on GDP across coal-dependent countries.

We divided the full sample into developed, developing, and ecological surplus/deficit countries. In developed countries, ecological footprint has a positive and significant effect on GDP (Beta =; p-value), but coal consumption is insignificant (Beta =; p-value), possibly due to an increase in the use of energy reduction strategies and the embracement of green energy systems. This

TABLE 7 Cointegration test (GDP model).

Approach	Test statistic	Z value	P value
Kao test	Modified Dickey-Fuller t	−2.9371[c]	0.0017
	Dickey-Fuller t	−2.6090[c]	0.0045
	Augmented Dickey-Fuller t	−0.7871	0.2156
	Unadjusted modified Dickey-Fuller t	−3.8560[c]	0.0001
	Unadjusted Dickey-Fuller t	−2.9979[c]	0.0014
Pedroni test	Panel-V	0.3946[c]	0.0000
	Panel-RHO	−2.1210[c]	0.0000
	Panel-t	−6.5220[c]	0.0000
	Panel-ADF	−2.8340[c]	0.0000
Westerlund test	Variance ratio	−2.1273[c]	0.0167

Significance level.
[a]10%.
[b]5%.
[c]1%.

suggests that developed countries promote economic activities at the expense of environmental sustainability. Also, the results for the developed countries indicated that trade openness (Beta =; p-value) has the largest effect, with DCPS promoting growth moderately. This result suggested that developed countries benefit from global trade integration.

In contrast to the results for the developed countries, developing countries benefit from increased coal consumption. Table 8 shows that a positive significant impact of coal consumption on GDP with both FMOLS (Beta =; p-value) and DOLS (Beta =; p-value) estimators. The results in Table 8 also shows that ecological footprint has a significant positive impact on GDP in developing countries (Beta =; p-value), suggesting higher economic growth in developing countries is associated with intense environmental degradation. Economic growth is reinforced by promoting trade openness and DCPS in developing countries. Results show that trade openness and DCPS have significant positive impacts on GDP. Thus, developing countries benefit from higher growth levels by being energy- and capital-intensive.

Furthermore, the results in Table 8 show that both coal consumption and ecological footprint have negative and significant effects on GDP. This suggests that the governments in ecologically surplus countries are sustainably managing coal use. In contrast, coal consumption and ecological footprint have positive and significant effects on GDP, indicating that ecologically deficit countries are growing at the cost of environmental degradation and stress. Similar to other groups, trade openness and DCPS maintain strong and positive impacts on economic growth.

3.6 Three stage least square results

3.6.1 Impact of coal consumption and ecological footprint on economic growth

For estimating the impact of coal consumption and ecological footprint on economic growth we employed the three-stage least square (3SLS). The 3sls model (1) of the full sample reported in Table 9 studies the impact of coal consumption and ecological footprint on economic growth. The results reveal that all variables are statistically significant at a 1% level. Coal consumption has a small but negative impact on economic growth, implying that a 1% increase in coal consumption will cause about a 0.07% decrease in GDP. However, the ecological footprint has a significant positive impact on economic growth implying that all things being equal, an 1% increase in coal consumption and ecological footprint will increase economic growth (real GDP) by 0.98%. Similarly, financial development has a positive influence on economic growth, indicating that a 1% increase in financial development will increase economic growth (real GDP) by 0.462%. However, the elasticities of the population are (−0.019) which indicates that a 1% increase in population will decrease the economic growth (real GDP) by 0.019% at a 1% significance level. Furthermore, trade openness has a positive but insignificant relationship with economic growth.

As far as developed and developing countries are concerned, the results of both developed and developing countries (as shown in model (1) of developed and developing countries reported in Table 9 exposes that ecological footprint has a significant positive impact on economic growth implying that all things being equal, an 1% increase in ecological footprint will increase economic growth (real GDP) by 0.982% and 0.953%. Though coal has a negative and significant impact on economic growth, i.e., a 1% increase in coal consumption will decrease the economic growth (real GDP) by 0.06% and 0.10% respectively. In addition, financial development has a positive and significant impact on economic growth in both developed and developing countries. Similarly, in developing countries, trade openness has a positive and significant impact on economic growth at 1% though positive but insignificant in developed countries. However, the population has a negative and significant impact on economic growth in developed countries at 1% but positive and insignificant in developing countries. Among all variables, both ecological footprint and financial development have high elasticities indicating that these two variables contribute most to economic growth.

The results of models (4 days) and (5e) disclose intriguing insights about the relationship between economic growth and various factors in ecological surplus and deficit nations. In the case of countries with an ecological surplus (model 4 days), the coefficients indicate that an increase in ecological footprint, financial development, and trade openness has significant and positive effects on economic growth. However, the coefficient for coal production is statistically insignificant, indicating that it has little effect on economic growth in these nations. Similarly, there is a small and statistically insignificant correlation between population and economic growth. In contrast to the results of ecological deficit countries presented in the model (5e), the coefficients for ecological footprint, financial development, and trade openness indicate significant and positive effects on economic growth. In addition,

TABLE 8 FMOLS and DOLS estimation results. The results reveal that coal consumption significantly boosts economic growth in the short term, but contributes to long-term ecological degradation. Moreover, ecological footprint negatively correlates with growth in most countries, suggesting unsustainable resource use. These findings highlight the need for cleaner energy strategies in coal-dependent economies.

Group		COAL	EF	TO	DCPS
Full Sample	FMOLS	0.02	0.42	0.19	0.1
		(4.74)	(35.32)	(86.96)	(17.59)
	DOLS	0.01	0.52	0.22	0.1
		(4.98)	(21.54)	(43.3)	(10.58)
Developed Countries	FMOLS	0.04	0.18	0.26	0.08
		(0.58)	(18.37)	(83.45)	(11.42)
	DOLS	0.02	0.33	0.3	0.06
		(4.6)	(18.9)	(44.52)	(7.49)
Developing Countries	FMOLS	0.01	0.68	0.12	0.12
		(6.29)	(32)	(38.25)	(13.53)
	DOLS	0.01	0.73	0.12	0.15
		(2.38)	(11.36)	(15.9)	(7.48)
Ecologically Surplus Countries	FMOLS	−0.02	−0.07	0.2	0.01
		(-7.79)	(0.92)	(59.54)	(3.01)
	DOLS	0.000	0.020	0.230	0.010
		(-1.970)	(2.670)	(34.370)	(5.100)
Ecologically Deficient Countries	FMOLS	0.03	0.57	0.19	0.13
		(9.73)	(39.88)	(66.42)	(18.44)
	DOLS	0.02	0.67	0.21	0.13
		(9.23)	(29.84)	(50.86)	(14.74)

the coefficient for coal production is positive and significant, indicating that it contributes to economic growth in these nations. Additionally, there is a modest but statistically significant correlation between population and economic growth. These results indicate that factors such as ecological footprint, financial development, and trade openness drive economic growth in both ecologically surplus and deficit countries. However, the effects of coal consumption vary considerably between countries.

3.6.2 Impact of ecological footprint and economic growth on coal consumption

The results for the relationship of coal consumption with economic growth and ecological footprint are presented in Table 10. The results disclose that economic growth has a significantly negative impact on coal consumption in all three samples at 1%, implying that all other factors being constant, an 1% increase in economic growth will decrease coal consumption by 0.45% in the full sample, 1.59%. in developed countries and 1.38% in developing countries. These results are in line with Shahbaz et al. (2018) for top energy-consuming countries, Azam et al. (2015) concerning ASEAN countries and Bildirici and Bakirtas (2014) in BRICS economies. Similarly, the coefficients of ecological footprint show a significantly positive impact on coal consumption in all three samples, implying that a 1% increase in ecological footprint will increase coal consumption by 0.43% in the full sample, 1.22% in developed countries and 1.11% in developing countries. As far as other variables are concerned, population and FDI have a positive and significant impact on coal consumption in the full sample and developing countries. However, in developing countries, trade openness has a significant positive impact on economic growth but FDI has an insignificant impact.

Moreover, models (4 days) and (5e) in Table 10 discloses the regression outcomes for ecological Surplus and ecological deficit countries. In the ecological surplus countries, the relationship between GDP and coal consumption is statistically significant and negative, indicating that a higher GDP is associated with lower

TABLE 9 The effect of coal consumption and ecological footprint on economic growth (3SLS estimation).

	Full sample	Developed countries	Developing countries	Ecological Surplus countries	Ecological Deficit countries
	Model 1(a)	Model 2(b)	Model 3(c)	Model 4(d)	Model 5(e)
Coal	0.0377[c]	0.0195[b]	−1.0645	0.1255	0.0117
	(0.039)	(0.045)	(0.356)	(0.817)	(0.676)
Ecological footprint	0.8539[c]	0.6018[c]	17.4719	−0.5078	1.1920[c]
	(0.000)	(0.000)	(0.270)	(0.820)	(0.000)
Financial Dev	0.0690[c]	−0.0063[c]	0.6323	0.1367	0.0865[c]
	(0.000)	(0.632)	(0.376)	(0.652)	(0.000)
Population	−0.0290[c]	0.2844[c]	6.4584	0.4135	−0.0952[c]
	(0.720)	(0.001)	(0.303)	(0.647)	(0.381)
Trade Openness	0.3290	0.3873	−4.4412	0.7427	0.2522[c]
	(0.000)	(0.000)	(0.333)	(0.597)	(0.000)
Constants	−0.4506	−7.2186[c]	−11.751[c]	1.5715	2.2599[c]
	(0.610)	(0.000)	(0.393)	(0.971)	(0.036)
Observation	731	387	344	172	559

Significance level respectively.
[a]10%.
[b]5%.
[c]1%.

coal consumption. There is a considerable positive correlation exists between ecological footprint and coal consumption, suggesting that countries with a larger ecological footprint tend to consume more coal. Additionally, population plays a significant impact, as a higher population correlates with increased coal consumption. Additionally, trade openness has a positive effect on the coal consumption of ecological surplus countries. In contrast, the ecological deficit model reveals a significant positive correlation between GDP and coal consumption, indicating that a higher GDP corresponds to higher coal consumption. Like the ecological surplus countries, the ecological footprint exhibits a positive correlation with coal consumption. Further, Population continues to exert a positive influence, whereas trade openness exerts a relatively lesser influence.

3.6.3 Impact of economic growth and coal consumption on ecological footprint

Table 11 exhibits the impact of economic growth and coal consumption on ecological footprint respectively for the full sample, developed countries and developing countries. The results disclose that except for developed countries, both economic growth and coal consumption have a significant positive impact on ecological footprint while for developed countries, GDP has a significant positive impact on ecological footprint but coal consumption has a significant negative impact on ecological footprint. These results are in line with past studies (e.g., Mensah et al. (2019)) that exhibit that consumption of fossil fuels leads to deterioration of environmental quality. Moreover, the coefficients of GDPsquare are positive and statistically significant for the full sample and developing countries which displays the non-existence of the EKC hypothesis, i.e (inverted U relationship). However, the coefficients of GDPsquare are negative and significant in developed countries which proved the existence of the EKC hypothesis. Besides, the coefficients of urbanisation indicate a significant positive impact on ecological footprint at 1%, while the coefficients of FDI are positive for the full sample at 10%. However, negative, and statistically insignificant for developed and developing countries.

Further, examining Model (4 days), the GDP has a highly significant positive relationship with the ecological footprint. This finding suggests that nations with a higher GDP have a larger ecological footprint. In contrast, the coefficient for GDPsquare is not statistically significant, indicating that the data do not support the EKC hypothesis. Similarly, the coal variable lacks statistical significance, indicating that there is no significant relationship between coal consumption and ecological footprint. Moreover, urbanisation emerges as a robust and significant predictor of ecological footprint in both model (4 days) and model (5e). This indicates that greater urbanisation correlates with a larger ecological footprint. In addition, both models (4 days) and (5e) demonstrate a statistically significant negative correlation between FDI and

TABLE 10 The effect of ecological footprint and economic growth on coal consumption (3SLS estimation).

	Full sample	Developed countries	Developing countries	Ecological Surplus countries	Ecological Deficit countries
	Model 1(a)	Model 2(b)	Model 3(c)	Model 4(d)	Model 5(e)
GDP	6.6626[c]	−34.4251[c]	15.3724[c]	−59.0699[c]	0.8950[c]
	(0.000)	(0.161)	(0.000)	(0.788)	(0.565)
GDP2	−0.1686[c]	1.0699[c]	−0.2883[c]	2.0240[b]	−0.1356[c]
	(0.000)	(0.013)	(0.000)	(0.809)	(0.000)
Ecological footprint	5.8449[c]	−4.9721[c]	−4.6958[c]	−8.9878[b]	11.2122[c]
	(0.000)	(0.225)	(0.215)	(0.143)	(0.000)
Trade Openness	−3.3976[c]	0.1273[b]	−4.1812[c]	0.6037[c]	−1.9729[c]
	(0.000)	(0.979)	(0.000)	(0.824)	(0.000)
Population	4.4014[b]	4.9463[c]	3.3238[b]	5.4469[c]	4.1027[c]
	(0.000)	(0.142)	(0.007)	(0.889)	(0.000)
Constants	−50.9616[c]	160.4249[c]	−65.5677[c]	335.7482[c]	−39.6799[c]
	(0.000)	(0.000)	(0.000)	(0.663)	(0.002)
Observation	731	387	344	172	559

Significance level respectively.
[a]10%.
[b]5%.
[c]1%.

ecological imprint. This suggests that countries that receive a greater amount of foreign direct investment have a reduced ecological footprint.

4 Discussion

This study investigated the relationship between economic growth (real GDP), coal consumption, and ecological footprint for 17 coal-based countries between 1980 and 2022. The findings of this study are summarized as follows: First, by looking at the results of unit root tests of Phillips-Perron test and ADF-Fisher, variables are stationary both at their level and first differences. Furthermore, the results of Hardi Z-stat represent that the null hypothesis of non-stationarity for whole panel variables can be rejected at levels I (0) and for some variables at first difference I (1), whereas Breitung t-stat shows the analysed variables are stationary at first differences. Second, the results for the Kao (1999), Pedroni (1999) and Westerlund (2007) panel cointegration test confirmed that the variables (economic growth, coal consumption, and ecological footprint) are cointegrated and hence possess a structural long-run relationship.

Third, results from FMOLS and DOLS estimators reveal significant positive relationships between coal consumption, ecological footprint and economic growth in developing and ecologically deficient countries. The results align with the findings of (Adebayo et al., 2023; Ding et al., 2023; Jin and Kim's 2018; Kanat et al., 2022; Alper et al., 2022; Arshad et al., 2022; Benjamin and Olusegun, 2020; Hassan et al., 2019), emphasizing that developing countries prioritize industrialization and economic growth, often relying on coal due to its affordability and accessibility. This fossil fuel reliance results in significant environmental costs, which outweigh the economic benefits due to excessive or inefficient coal consumption, highlighting the environmental cost of energy-driven growth. In addition, economic growth drives higher consumption of energy and natural resources, leading to environmental degradation. Further, the usage of outdated technologies exacerbates this by increasing energy intensity and environmental harm (Wang et al., 2019).

Thirdly, the results of three-stage least square (3SLS) showed that coal consumption have a significant negative impact on the economic growth for all samples (Full, developed and developing) but positive for both ecological surplus and deficit countries. Similarly, for all samples (full, developed, developing ecological surplus and deficit countries), the ecological footprint has also a significant positive impact on economic growth, highlighting the extreme natural resources consumption, industrialisation, and infrastructure for rapid economic development, as such continued

TABLE 11 The effect of coal consumption and economic growth on ecological footprint (3SLS estimation).

	Full sample	Developed countries	Developing countries	Ecological Surplus countries	Ecological Deficit countries
	Model 1(a)	Model 2(b)	Model 3(c)	Model 4(d)	Model 5(e)
GDP	0.6048[a]	0.9633[a]	0.5200[a]	−0.3970[a]	0.5579[a]
	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)
Coal	0.0979[a]	0.1014[a]	−0.0485[a]	−0.0605	0.0832[a]
	(0.000)	(0.000)	(0.000)	(0.020)	(0.000)
Urbanisation	−0.2443[a]	−1.2388[a]	−0.1236[a]	−0.2928[a]	0.1717[a]
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
FDI	0.0232[b]	0.0092	−0.0262	0.0276[c]	0.0155[c]
	(0.001)	(0.302)	(0.000)	(0.008)	(0.023)
Constants	0.1355[a]	15.3898[c]	−1.6614[a]	11.3656[b]	−0.7076[c]
	(0.789)	(0.000)	(0.000)	(0.000)	(0.193)
Observation	731	387	344	172	559

Significance level respectively.
[a]1%
[b]10%.
[c]5%.

efforts and checks and balances must be in place to ensure institutionalized environmental quality policies and initiatives in coal-based countries. Further, for (Full, developed, developing and ecological surplus countries, the results of the influence of economic growth and ecological footprint on coal consumption revealed that economic growth has a significant negative influence on coal consumption but a positive impact on coal consumption for ecological deficit countries. This is accredited due to the reason that countries may have reached the stage where rates of savings are higher as compared to the rate of consumption. These accumulated funds have been used for energy-efficient technologies and to develop high technological industries. Also, learning from past experiences, these countries may have shifted from fossil fuel to renewable energy consumption or have implemented energy-efficient technologies to curb environmental damage. The results are consistent with Acheampong (2018) in the case of 116 countries, and Khan et al. (2019) in the case of 193 countries. However, ecological footprint coefficients are positive and significant, i.e., has a positive impact on coal consumption. This is attributed due to the reason that environmental deterioration through emission, ecological footprint, etc., are direct penalties for inefficient fossil fuel energy. These results are confirmed by Dong et al. (2019) for 128 countries across the globe.

In addition, the impact of economic growth and coal consumption on ecological footprints discloses that both economic growth and coal consumption have a significant positive impact on ecological footprint, implying that these countries are fossil-dependent countries. These results are justified by the reason that current renewable energy demands are still lower than required for these countries. Therefore, the rest of the energy demand is met by fossil energy resources for economic development. Further, these countries may lack the technologies that assist in the transition to renewable energy. The results are in line with Shahzad et al. (2021) in the case of the United States, Chen et al. (2019) in 16 CEE countries and Awosusi et al. (2023) in case of Japan., Adebayo et al. (2021a) in South Africa. However, the results are in contrast with Somoye and Ayobamiji (2024), who found that energy consumption and economic growrh are crucial driver of environmental sustainability. Furthermore, except for developed countries, it rejects the EKC hypothesis, i.e., an increase in economic growth increases ecological footprint up to a certain time, then finally declines. This is due to the reason that developing countries are still at the stage of development, there is a lack of energy-efficient technologies and proper environmental laws and regulations, these can protect the environment degradation. However, developed countries have strong environmental regulations, technological innovation and research which assist them to restrict the ecological footprint. The results are in line with Altıntaş and Kassouri (2020) in the case of ten European economies, Ren et al. (2021) with and Khan et al. (2019) in 193 countries.

5 Conclusion

This study provides an in-depth analysis of the nexus between energy-led growth and environment-led growth in top coal consuming countries. The results demonstrate that both coal consumption and ecological footprint are crucial drivers of economic growth in top coal-consuming countries. Hence, to accelerate economic growth, continued reliance on fossil fuels like coal, exacerbates environmental degradation in these countries. The study suggests that to align with the objectives of COP-28, focussed in transition away from fossil fuels and ensuring to maintain the global temperature within the 1.50 threshold, policymakers should focus on a gradual yet decisive transition from coal to renewable energy to address the environmental impacts of fossil fuel dependency, efforts must be intensified to boost the proportion of renewable energy in the overall energy mix. The concerned government should offer incentives for renewable energy infrastructure, green and renewable energy initiatives, investing in research and sustainable development, and removing regulatory hindrances. Additionally, policies that promote energy efficiency should integrate advanced energy-saving technologies, conducting public awareness campaigns, and enforcing stringent energy efficiency standards, enabling the continued use of conventional energy sources, including coal, in a more sustainable manner. Also, stakeholders must prioritize funding and intensify research and development efforts in cleaner coal technologies and carbon capture and storage (CCS) to shift towards more sustainable energy sources. Furthermore, stricter environmental regulations should be enforced to limit the adverse impacts of fossil fuel consumption. To ensure environmental quality, the respective governments should enforce penalties for non-compliance, emissions reduction targets, monitor pollution levels, promoting energy efficiency in industrial processes.

This study faces data availability limitation across the top seventeen coal-consuming countries. Additionally, geographical, and cultural differences among the countries may limit the generalizability of the results. Future research should incorporate additional variables such as technological innovation, energy policy, and energy efficiency to reduce pollution further and enhance sustainable growth. Additionally, future studies should conduct cross-region comparisons based on low and high coal consumption or those transitioning to renewable energy, allowing for tailored policy interventions. The empirical findings highlight the necessity of adopting a comprehensive energy policy that balances economic growth with environmental sustainability. To achieve sustainable development, coal-consuming countries should focus on accelerating the transition to renewable energy, improving energy efficiency, and enforcing strong environmental regulations. These measures can lead to enhanced quality of life for citizens while supporting long-term economic stability. The insights from this research provide crucial guidance for policymakers and stakeholders dedicated to fostering a sustainable energy future in coal-dependent nations.

Data availability statement

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

Author contributions

YA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review and editing. SR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We acknowledge that the content of our manuscript have previously appeared online as a preprint in the Research Square repository. The link is avaiable at: https://www.researchsquare.com/article/rs-3216141/v1.

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.

Publisher's note

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